SKF AL68T075

SUPPLEMENTAL REPORT OF TASK ORDER NO. 5

MEASUREMENT OF LUBRICANT FILM THICKNESS IN HERTZIAN CONTACTS

by

G. E. Allen, L. A. Peacock and W. L. Rhoads

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7912

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

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AL68T075

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I. ABSTRACT

Reported herein are two instrumentation systems for monitoring ball-bearing oil-film thickness, which were developed and tested during Tasks 3 and 5 of Contract NAS3-7912. These systems are capable of measuring the condition of the elastohydrodynamic (EHD) lubricant films in operating ball bearings during high-speed, high-temperature operation (up to 43,000 rpm and 700°F).

The first technique is a capacitance method which measures, under full EHD film conditions, the total capacitance across the rings of the test bearing. This capacitance represents a parallel arrangement of a series of two capacitors, consisting of the Hertzian contacts between the several balls of a bearing and their raceways as plates, and the lubricating film as dielectric. Expressions relating this capacitance to lubricant film thicknesses were derived and are used in the interpretation of the experimental data.

The second technique is a method which measures the electrical conductivity across Hertzian contacts. This technique yields the instantaneous values and time average of a voltage placed across the parallel and series arrangement of Hertzian contacts between the balls and bearing rings, described above. It provides input data for expressions relating average voltage to asperity non-contact-time, and subsequently, to the average film thickness in bearings operating under partial EHD lubrication conditions.

A detailed discussion of representative experimental data is given to illustrate both the above methods.

II. THE CONTACT CONDUCTIVITY TECHNIQUE

A. Background

Electrical conductivity between rolling or sliding surfaces separated by a lubricant film has for some years been established as a means of instantaneously monitoring the occurrence of asperity contact between surfaces (1-3)*. It is the purpose of one phase of Task 3 to develop a technique for experimentally determining the time average of a voltage placed across the races of a ball bearing operating under thrust load at high speeds and temperatures, and to derive expressions which functionally relate the average value of the voltage-time function, empirically determined, to the percentage of time that no metal-to-metal contact occurs in the bearing. From this "no contact" time fraction, the average lubricant film thickness is determined.

In the past, a technique measuring the time average of contact occurrences between asperities on balls rolling in a "Barwell" type rolling 4-ball tester has been perfected in the SKF Industries Research Laboratory (2). Parameters such as lubricant film thickness between rolling surfaces, and number and duration of asperity contacts, were extracted from the data obtained.

The conductivity technique utilized in the 4-ball tester is a relatively simple and direct one which has been described in several publications, e.g., in (2). In principle, this method consists of applying a low (100 mv) DC voltage across the Hertzian contact under study, placing a current limiting resistor (several kilohms) in the circuit and monitoring the voltage-time function across the contact. The circuit is shown in Enclosure 1 . During rolling or sliding under conditions of partial elastohydrodynamic lubrication (i.e. when asperities penetrate the EHD film), the electrical conductivity between the surfaces intermittently rises to a high value, and hence the voltage across the contact drops to practically zero. The periods of high conductivity are attributed to encounters between asperities on the opposing surfaces which are high enough to penetrate the elastohydrodynamic film of lubricant. Thus the time average voltage is a function of the time fraction of uninterrupted elastohydrodynamic film existing in the Hertz contact, i.e. it

* Numbers in parenthesis refer to references at the end of this report.

decreases as the film is interrupted more often by asperity contact formation. On the simplest assumption that the contact conductivity is always either zero or infinite depending on whether or not the asperities are in contact, the voltage ratio V/Vo, expressing the measured voltage as a fraction of the applied voltage, is simply equal to the time fraction, T/To during which there is no contact. A statistical theory has been developed, (2), which relates T/To to the dimensionless film thickness h/σ where h = average "uniform"* film thickness, and σ = composite rms surface roughness of the two surfaces in contact. Parameters affecting this relationship are the shape and size of the Hertzian contact area under study, and frequency distributions of the surface asperities (amplitudes and spacings) as defined in (2).

Most of the earlier work, using the conductivity principles described above, was performed with a low level DC source across the contact. It is preferable however to utilize an AC source in high-speed, high-temperature bearing testing, in order to eliminate the effects of thermally generated DC voltages, and 60 Hz electrical noise produced by motors and heaters which, of necessity, are in close proximity to the monitored bearings. For this reason, AC techniques were later developed in the SKF Research Laboratory (4). Using those techniques, it has been shown that in a Barwell four-ball tester, correlation between conductivity data acquired with AC and DC conductivity techniques is excellent (within 5%). Enclosure 2 shows a block diagram of the test set-up used for this correlation and Enclosure 3 shows typical test data obtained for a sequence of increasing speeds in the Barwell tester for both techniques. A more sophisticated technique, the instrumentation of which is detailed in the next section, was developed during Task 3 of this contract for contact conductivity monitoring of 7205 size bearings, operating under extreme loads, speeds, and temperatures.

B. Instrumentation

A block diagram and a photograph of the test set-up used for the acquisition of AC conductivity data for 7205 size bearings operating in extreme environments are shown in Enclosures 4 and 5 respectively. Block diagrams of the relay switching circuitry and its function are shown in Enclosures 6A and 6B. A photograph and layout sketch of the test machine are shown in Enclosures 7 and 8 respectively. A drawing of the test bearing is shown in Enclosure 9.

*The uniform film thickness is that prevailing over the Hertzian contact area with the exception of the outlet constriction. See (15, 16).

A sinusoidal voltage of 500 Hz frequency and 200 mv peak-to-peak amplitude is impressed across the outer and inner races of the bearing via a Krohn Hite, Model 440A audio oscillator through a current limiting resistor which can be selected to any one of a number of values between 5-100 KΩ. Electrical contact to the outer race of the bearing was provided, (for the data reported here), by a spring loaded thermocouple sheath, which with adequate insulation, is passed through the bearing housing, the load plug, and a specially designed heat treated polyimide insulator as in Enclosure 10. The thermocouple was thus used to monitor both electrical conductivity and bearing temperature. Later a permanent and more reliable system for providing contact to the outer race of the bearing was developed as shown in Enclosure 10. Electrical contact is supplied to the inner race through two pairs of wire brush slip rings, having operating lives of several hours, which make contact with the gold plated drive quill as shown in Enclosure 11. A light nitrogen blanket, which prevents particle contamination of the brush contacts, is afforded the brush-quill interface through a plexiglass enclosure shown in Enclosure 11. A splashguard, also shown in Enclosure 11, is designed to prevent gearbox oil from leaking onto the contact surfaces. The instantaneous voltage variations across the array of Hertz contact areas of the bearing are observed on an oscilloscope.

Digital readout of the time average of the applied voltage is established in the following way. The contact voltage across the bearing is amplified, by 20 db, by a Hewlett Packard general purpose amplifier, Model 450A, having a frequency response of 5 Hz-1MHz and an input impedance of one megohm. A blocking capacitor (0.22 μf) at the input of the amplifier prevents the passage of DC voltages.

The feasibility of using both active, (Krohn Hite, Model 330 M) and passive, (Allison, Model 2 ABR) band pass filtration techniques, for the elimination, from the monitoring system, of 60 Hz electrical "noise", has been investigated. It has been established that each method is rather seriously limited by its characteristic frequency response and phase-shift properties. The frequency response required for the monitoring system is quite stringent in that frequencies from at least 500 Hz to approximately 1 MHz must be passed without excessive phase or amplitude distortion. This becomes evident if one analyses the asperity contact duration and corresponding signal frequencies generated in these high speed tests. Due to the fact that the available filters did not have the required response their use was abandoned. The possible use of various types of 60 Hz rejection filters, having the desired response, is currently being investigated.

After half wave rectification, (by a IN67 diode), digital readout of the time average of the monitoring signal over a 1 second time interval, is provided by a Vidar, Model 260, voltage to frequency converter, (which provides the necessary smoothing of the rectified input signal), in conjunction with a Hewlett Packard, Model 5214L, frequency counter.

The relays, shown in Enclosure 6A permit monitoring of the contact quality of the slip ring assembly by the imposition of the contact conductivity monitoring voltage across each slip ring pair as shown in Enclosure 6B.

C. Determination of Operating Parameters

In previous work, operating parameters such as the required values of the current limiting resistor and operating signal level have been established for both the DC and AC techniques used in the Barwell type rolling 4 ball tester. For the present tests on bearings operating under extreme conditions, where AC techniques are indicated, additional phenomena (e.g. capacitive reactance of the test bearings, the test machine, and test leads) must be evaluated in order to insure the fidelity of the measured time average of the applied signal.

The following are significant conditions which must be satisfied in all contact conductivity testing techniques. An equivalent electrical circuit of the bearing and test set-up is shown in Enclosure 12.

1. Furey (1) and SKF (2) have shown that it is necessary to ensure that the voltage applied across the Hertzian contact is below a few hundred millivolts, in order to eliminate spurious conductivity phenomena caused by the dielectric break-down of thin EHD lubricant films. Hence, the input signal level is set at 200 mv peak-peak.

2. It was also shown in (2) that it is necessary to keep the current relatively low, i.e. series resistance high, in order that current once established through an asperity contact, is not maintained for a significant length of time, through a heavily ionized path in the lubricant, which is perpetuated by the thermal action of the current itself.

3. Holm (5) and recently SKF (6) has shown that although the ohmic resistance of metal to metal contacts between asperities is generally only a few ohms, there are contact conditions, (e.g. the presence of surface layers) which generate substantial resistances.

In the test conditions encountered here, these contact resistances are expected to be of the order of several hundred ohms. Thus, in order that the time average of the voltage applied across the Hertzian area remain undistorted by voltage excursions, which, because of non-zero contact resistances, do not fall to zero during periods of contact, the current limiting resistance must be an order of magnitude larger than the expected value of these finite contact resistances.

Conditions 2 and 3 above, then, constrain the current limiting resistance to values above 5 kilohms. This value permits a peak current of 20 microamperes at 100 mv. peak signal voltage, which is believed to be low enough to prevent the difficulties cited in 2. It is also sufficiently large compared to contact resistances of several hundred ohms.

There are additional conditions which must be met by the specific AC test system used in Task 3 and which, along with the effects discussed above, manifest themselves as boundary conditions on the test parameters of operating frequency and current limiting resistance, and will be discussed below.

4. After asperities have broken contact, the bearing equivalent circuit, as shown in Enclosure 12, is essentially a series circuit composed of the current limiting resistance and the combined capacitance of the test bearing, the test machine and the test leads. Since the fidelity of the voltage-time function is imperative for meaningful interpretation of the time average of the voltage across the contact area, the time constant of this series circuit plays a most significant role in the determination of the upper limit of the value of current limiting resistance. Ideally, this time constant should be several times less than the average time between contact occurrences(approximately 6 micro seconds as calculated in Appendix I). It was shown empirically, from test data to be discussed in Sections IV and V, that the deleterious effect, arising from violation of condition 4 , begins to manifest itself at current limiting resistance values above 15 kilohms. It is however, possible to operate with some success up to 50 kilohms resistance.

In addition to the time constant of the circuit operating when the asperities break contact, manifested by gradual increase of contact voltage with time, there is, as is seen from Enclosure 12, a finite voltage decay time associated with the onset of contact occurrence. It is however a function of the contact resistance, which is small relative to the current limiting resistance, and as such its effect on the observed V/Vo is of lower order of magnitude and thus less significant than the voltage buildup time at contact interruption discussed above.

From the above, upper and lower bounds for current limiting resistance values are established at 50 kilohms and 5 kilohms respectively. The question of the resistance to be used within these limits will be discussed later.

5. Since it is essential that the voltage Vo across the Hertzian area under full EHD lubricant film conditions be known in order to establish the V/Vo ratio, and since there can exist mechanical test conditions under which full EHD operation is not realized anytime during the test, Vo must be capable of being referenced to V_{AG}, the applied voltage. That voltage, V_{AG} (Enclosure 6B), can be measured by interruption of the circuit. This requirement is treated more thoroughly in Appendix II wherein it is shown to be desirable that Vo be very nearly equal to V_{AG}, i.e. that the combined capacitive reactance of the test bearing, machine, and connecting cables be much greater than the current limiting resistance (i.e. that $X_{CT} >> R_{CL}$). The proper choice of operating frequency permits satisfaction of this inequality. From Appendix II it is seen that, using 50 kilohms current limiting resistance in a "worst case" analysis, a frequency of 500 Hz readily satisfies this condition. It is also shown that lower values of frequency and current limiting resistance are more desirable in this respect. It is also desirable, on the other hand, to keep the signal frequency high enough so that interference by 60 Hz line frequency and its harmonics is avoided. A signal frequency of 500 Hz was therefore chosen.

In light of the above constraints, the test configuration shown in Enclosure 4 was ultimately chosen for testing during Tasks 3 and 5. The operation of the system, the results obtained, and methods of interpretation are discussed in the following Section D and further in Section V and VI.

D. Data Reduction

Reduction of AC conductivity data to the dimensionaless h/σ parameter (ratio of lubricant film thickness to bearing composite rms surface roughness) which describes the condition of the lubricant film proceeds as follows:

AC conductivity data are recorded as percentages, where 100% corresponds to a full EHD lubricant film and numbers less than

100 correspond to the time fraction (percentage) during which a full EHD film exists everywhere in the entire bearing, as previously described in (2). As an approximation, the voltage average fraction V/Vo is set equal to the non-contact time fraction T/To (total). This approximation is valid only if proper balancing of time constants (voltage rise and fall) is maintained. This is done by obtaining data at two bracketing current limiting resistance values (5 and 50 kilohms) and at one intermediate value (15 kilohms). Further discussion of this problem is presented in Section VI of this report.

Since the test bearing is a multi-contact configuration and not a single contact, a relation is needed which relates the no contact time fraction for the entire bearing, T/To (total) to the no contact time fraction for a single contact, T/To (single contact). A second relation is also needed which relates T/To (single contact) to the dimensionless film parameter, h/σ. Both relations which are derived in Appendix III are used to compute the AC conductivity data reduction curves, given in Enclosure 13, which give T/To (total) - also designated as T/To (across rings) vs. h/σ for a 7205 bearing operated at 43,000 rpm at thrust loads of 300 lbs. and 459 lbs.

To insure that no contact occurs in the test bearing through the cage, a special insulating high temperature polyimide cage is used in place of the standard silver plated M-1 steel cage in the test bearing. The polyimide material is manufactured by DuPont and is designated Vespel SP-1. Appendix IV contains some properties of this material: it allows continued bearing operation at 600°F and a few hours operation at 700°F. Enclosure 14 shows pictures of both a new and a failed polyimide cage.

III. THE CAPACITANCE TECHNIQUE

A. Background

When a bearing is operating in the full elastohydrodynamic lubrication region (i.e. with practically no contact between surface asperities), contact conductivity techniques, as described in Section II above, are incapable of yielding quantitative data related to the film thickness. Hence, under full film conditions other techniques for monitoring film thickness must be employed. A technique which has as its basis the measurement of the capacitance between the bearing components, (i.e. rolling elements and races), has been developed in the SKF Industries Research Laboratory. Conceptually it proceeds as follows:

1. As shown in Enclosure 15A and 15B, an operating 7205 bearing can be considered to consist of the parallel arrangement of series-connected pairs of capacitors. These capacitors are formed by the Hertzian contacts between the rolling elements and the raceways as plates, and the lubricating film as dielectric. The capacitance between races can be measured on a conventional capacitance bridge.

2. Values of capacitance thus determined provide input data for relationships, from which film thickness can be calculated for a known bearing operating at specified conditions. These relationships were derived using a method by Dyson (9) giving film thickness vs. capacitance for a two dimensional contact. SKF has extended this technique to three dimensions as shown in Appendix V, in which both circular and elliptical contacts are considered.

The capacitance technique has been tested in the SKF Laboratory in a Barwell rolling four ball tester as described in (4). It was found that film thickness values thus determined were within 20% of the theoretically calculated values, and within 30% of values empirically determined by contact conductivity techniques, in those film thickness regions of partial EHD lubrication, where both techniques can be used. Enclosure 16 shows graphically a comparison of film thickness data obtained by conductivity and capacitance techniques, with those predicted theoretically. The instrumentation for a capacitance method useable for complete bearings, was developed in Task 3 and is described below.

B. Instrumentation

A Boonton Electronics Corporation, Model 75C, Capacitance Bridge is utilized for all capacitance measurements. It provides a signal across the test bearing which is continuously variable in amplitude from 1mV-3V, and through a continuously adjustable frequency range of from 5 KHz to 500 KHz.

A simplified schematic diagram of the bridge is shown in Enclosure 17. The output signal of an RC oscillator is fed to a modified Young Bridge. The bridge output, first amplified by a high-gain frequency selective amplifier, is rectified and used to actuate a "Null Indicator" Meter.

Electrical connection of the Capacitance Bridge to the test configuration, (inner and outer races of the bearing), is accomplished through two twenty-five foot lengths of low capacitance (14 pf/ft) coaxial cable (Belden Model RG 58), which make contact with the bearing races as described in Section II B.

C. Data Reduction

Reduction of capacitance data to the dimensionless h/σ parameter (ratio of lubricant film thickness to bearing composite rms surface roughness) which describes the condition of the lubricant film proceeds as follows:

Capacitance data is measured on the capacitance bridge and is recorded in picofarads. They can directly be related to the lubricant film thickness, h, if the Hertzian contact geometry and dielectric constant of the oil is known (Appendix V). A graph of capacitance vs. film thickness determined by the method presented in Appendix V is shown in Enclosure 18. The rms surface roughness of the bearing components is measured and from these values, the composite rms surface roughness value, σ , for each test bearing is calculated. Knowing both the film thickness h and the composite rms surface roughness, σ , the dimensionless parameter h/σ is obtained by division.

In order to determine the bearing capacitance, an assessment must be made of the contribution of the capacitance introduced by the test rig. The test rig is in a parallel circuit arrangement with the test bearing; therefore, the two capacitances are additive. Once the total capacitance is measured, the capacitance of the test bearing is found by subtracting the rig capacitance from the total capacitance. The test rig capacitance is found by measuring the capacitance of the completely assembled rig including the test bearing inner ring, outer ring and polyimide cage but omitting the twelve bearing balls. Measurements have shown the rig capacitance to be 80 picofarads.

IV. TEST PROCEDURE

A. System Performance Check

Prior to data acquisition, both the conductivity and capacitance systems described in II and III above, were subjected to test procedures designed to simulate bearing performance.

A.1 Capacitance System Check

The capacitance bridge readout was checked, simply, by its response to the insertion of standard mica capacitors of known value in place of the bearing, i.e. in close proximity to the test rig, at the rig end of the connecting cable. Capacitance values approximating those expected in the operating bearing (173 to 345 pf) were used. The capacitance readings obtained on the bridge were at all times repeatable and within the rated tolerances of the capacitors' nominal value.

A.2 Conductivity System Check

The fidelity of the conductivity monitoring system, i.e. the response of the amplifier, rectifier, and readout system, to the electrical analog of contact occurrences, was determined as follows: Rectangular pulses produced by the combination of a Tektronix waveform generator, Model 162, and a Tektronix pulse generator, Model 161, were added, across an isolating resistor, to a 500 Hz sinusoid, produced by the Audio Oscillator of the system as shown in Enclosure 19. The sum was then applied to the Monitoring System, i.e. amplified, rectified, etc. and its readout was compared to the calculated expected values for pulse duration of 3, 5, 10, 15, 20, 30 and 50 microseconds at periods of 100 and 1000 microseconds. It is seen from Enclosure 20, that the readout is within 8% of the expected value. (Although the Vidar, Model 260, voltage to frequency converter has a maximum full scale output frequency of 100 KHz, its' readout sensitivity for rectified inputs extends into the megacycle range due to an integrating capacitor located between its preamplifier and voltage controlled oscillator.)

Undesirable 60 Hz amplitude modulation of the conductivity signal was minimized by the utilization of D.C. operated relays and coaxial cable, throughout the system. Modulation was thus kept within 10%, even for the highest (50 kilohm) current limiting resistance used. Since the readout is obtained by rectification and averaging, the 10% 60 Hz modulation described produced no more than 1% readout variation when observed with the bearing operating under full film conditions.

B. System Operating Procedure

At the start of each test, both the capacitance and conductivity systems are checked out, after a one-half hour warm-up period for satisfactory component performance. Output waveforms at all interconnection terminals are checked with an oscilloscope. Relay operation and bearing outer ring contact stability are likewise checked. The capacitance bridge is balanced. The output of the audio oscillator in the conductivity circuit is checked with an oscilloscope for both amplitude and frequency stability. The Vidar analog to digital converter is equipped with an adjustable scaling factor. It is adjusted to read 100 for the open circuit condition, thus permitting direct readout of V/Vo in percentages.

Prior to each film parameter measurement, the test bearing outer race temperature and the performance of the slip ring assembly are monitored, as described in Section II-B, above. Deterioration of the slip ring to drive quill electrical conductance leading to a monitored V/Vo percentage of 2% or greater (R_{CL} = 5 KΩ) indicates the need of adjustment in slip ring assembly or a change of brushes.

While the bearing is operating, the output of the conductivity amplifier is visually monitored on a Tektronix Model 564 oscilloscope with "memory" capability. Loss of electrical contact at the outer race is evidenced by relatively lengthy and intermittent dwell periods (millisecond range) in the disconnected and connected states, and as such, is easily distinguished from asperity contact breaks.

Photographs of the conductivity signal can be procured from the face of the Memory Scope via a Polaroid Model 2620 camera in conjunction with its oscilloscope attachment. Representative photographs for various V/Vo values are shown in Enclosure 21.

V TEST RESULTS

A. System Operating Range

AC conductivity measurements yield h/σ values when less than a full EHD lubricant film exists in the contacts; that is, when opposed asperities are penetrating the film and contacting each other. The capacitance measurements yield h/σ values when a full film exists where practically no asperity contacts occur (which would cause the measuring signal to be shorted across the contact). In practice there exists a fairly sizeable overlap region where capacitance can be measured simultaneously with conductivity despite the presence of contact occurrences.

This can be seen by comparing the h/σ values determined from the curves in Enclosure 13 for conductivity measurements to the h/σ values determined from the curve in Enclosure 18 for capacitance measurements. The overlap region extends from about T/To (total) = 80% to T/To (total) = 99% where h/σ values obtained from both methods are in good agreement as shown in Enclosure 23. Below T/To (total) = 80% only AC conductivity is to be believed for reasons set forth in Sections II and III of this report. Above approximately T/To (total) = 99%, conductivity results are unreliable and capacitance results are acceptable.

B. Film Measurements

Film measurements were made with the AC conductivity and capacitance systems described with 7205 VAP (M50 steel) bearings which were not black oxide coated, using Mobil XRM-109F hydrocarbon lubricant. Some AC conductivity measurements were also made with uncoated 7205 VAR (WB49) bearings and DuPont PR-143 lubricant.

Testing with Mobil XRM-109F lubricant was conducted at 43,000 rpm, 300 lbs. thrust load, and bearing temperatures from 415°F to 700°F. The results of this testing are presented in Enclosure 23 in the form of h/σ vs temperature plots. The back-up data for these plots are contained in Enclosure 24 along with the required data reduction procedures outlined in previous sections. The plots show, first of all, that film thickness generated with this lubricant are approximately one-half as great as theoretically predicted values. Secondly, the plots show that the AC conductivity and capacitance techniques are in fairly close agreement in yielding h/σ values.

Both AC conductivity and capacitance plots show the expected decrease in film thickness with increasing temperature up to about 575°F. However, the results also show an unexpected increase in film thickness from 575°F to 700°F. This phenomenon of increasing film thickness with temperature, is not fully understood at this time. A more complete discussion is presented in (13).

The results of testing with DuPont PR-143 lubricant are contained in Enclosure 22 in the form of illustrative oscillograms accompanied with suitable description. AC conductivity data was acquired at two speeds (24,000 rpm and 39,000 rpm) to show the effect of speed on EHD lubrication with three values of resistance (5, 10 and 50 kilohms). A thrust load of 459 lbs. was used and temperatures ranged from 550°F to 650°F. Conductivity data is recorded (V/Vo measured) for each resistance value and the corresponding h/σ parameter is obtained from Enclosures 13 and 15 as described in Section II-D. In Enclosure 22, rows A and B are repeats of each other as are rows C and D. The only difference here, in addition to slight temperature variations (10°F max.), is that rows B and D were taken at less horizontal magnification than rows A and C to show a greater portion of the AC measuring signal. Vertical magnification is specified for each oscillogram. From the data presented, it appears that the lubricant film thickness, contrary to isothermal EHD theory, decreases as speed is increased. The oscillograms show more contact occurrences at higher speed (39,000 rpm) than at the lower speed (24,000 rpm). However, the bearing temperatures at the higher speed were at least 50°F hotter than for the lower speed. Apparently viscosity change due to increased temperature outweighed the effect of the change in speed. The increased temperature at the higher speed is due to a combination of a closed, small capacity recirculating oil system and increased bearing thermal heat generation with increasing speeds. For a discussion of pertinent details of the test rig and operating procedure see (7, 11).

For the AC contact conductivity measuring system the values of 5 and 50 kilohms were selected as described in Section II-C, as being the lower and upper limiting values of current limiting resistance (R_{CL}). For the data collected with PR-143 fluid, 10 kilohms was used as an intermediate resistance value. Based on oscillograms of Enclosure 22 and other experience a value of 15 kilohms was later selected as being a more appropriate resistance value for reasons to be given below.

VI. DISCUSSION AND INTERPRETATION OF RESULTS

A. Conductivity Data

Rather significant variations (up to 30%) exist in h/σ values obtained with three values of current limiting resistance (i.e. R_{CL} = 5, 15 and 50 kilohms). This is illustrated in the data and photographs of Enclosure 23 which were taken at 5, 10, and 50 kilohms. The necessity of acquiring data using values of this resistance throughout the "permissible" (as explained in Section II) range of 5-50 KΩ is best understood by an examination of Enclosure 25 in which an "ideal" contact occurrence is shown compared to its experimental counterpart. (An ideal contact occurrences is a hypothetical asperity contact occurrence of zero ohm contact resistance producing an intermittence in the 500 Hz monitoring sinusoid with zero voltage decay and rise times, and zero V/Vo during contact).

Enclosure 26 shows photographs (taken from the face of the monitoring oscilloscope) of contact occurrences with values of current limiting resistance of 5, 15, 50 kilohms. It is seen from Enclosure 25 that for the "ideal" occurrence (where $R_{CL} = R_C = 0$) the voltage ratio, (V/Vo average) is identical to the no contact time fraction (T/To average) over a given time interval. The experimental contact, on the other hand, has three competing "waveform distorting" mechanisms, all of which are functionally related to the values of current limiting and contact resistances.

First, at the onset of contact, the discharge time associated with the capacitor composed of the capacitance of the test leads and test machine ($C_{TL} + C_{TM}$) through the contact resistance (R_C) allows, throughout the period of decay (δ_1 in Enclosure 25), a non zero voltage which enters the electronic computation of V/Vo average and inflates its value.

Secondly, a contact occurrence having finite electrical resistance permits the establishment of electrical potential across the bearing during the periods of contact. This non zero value of V/Vo during the period of contact (V, in Enclosure 25) further inflates the V/Vo average. (The amount of this V/Vo inflation is directly related to the ratio of the contact resistance to the current limiting resistance.)

Thirdly, the charge time of the capacitor composed of the capacitances of the bearing, machine, and test leads (C_{TL}), through the current limiting resistance (R_{CL}), impedes the rise of the monitoring voltage to its impressed value after asperities have broken contact, (throughout the period δ_2 in Enclosure 25). This phenomenon is, of course, in opposition to the two aforementioned modes of "waveform distortion" and as such tends to deflate the measured average values of V/Vo.

It is apparent from the above, that in order to analytically establish a preference for a particular value of R_{CL}, knowledge of the average value of the contact resistance is necessary. The literature (Holm (5), McCool (12)), state however, that values of contact resistance in test systems similar to that used in Task 3, can range from fractions of an ohm, due to constriction resistance in metallic asperity contacts to many kilohms due to tunnel resistance through boundary oil or oxide films.

For this reason a preferred value of the current limiting resistance can not be obtained theoretically and conductivity data were accumulated throughout Task 5 at three values of current limiting resistance. Analysis of Task 5 contact conductivity results will reveal which, if any of the three values used is to be preferred for the test system described herein.

B. Film Thickness Determination

The information reported herein indicates that the measuring system developed in this Task is capable of monitoring the condition of the lubricant film in operating bearings. Lubricant film thickness of operating bearings can be derived and changes in the lubricant film thickness due to temperature changes or other transient conditions such as changes in oil flow and bearing load can be observed.

The film thickness measured is only about half of the isothermally computed value for the test conditions.

The discrepancies between measured and theoretically predicted film thickness are most probably caused by thermal effects encountered in testing at such relatively high speeds. A great deal of ball slip occurs at high speed which locally increases the oil temperature and decreases oil viscosity. The computational method used for determining film thickness outlined in (7) is strictly isothermal. It is known that thermal effects cause a reduction in the operating film thickness causing it to be less than theoretically predicted values due to the spinning heat generated. The greater the thermal effects, due to high speeds, the greater the downward departure from predicted film thickness values.

In (8) a method is presented by which the expected downward deviation, between theoretically predicted (isothermal) and actual film thickness can be estimated from the test conditions. Utilizing this approach, for the test conditions cited in this report, a thermal reduction factor of approximately 0.9 (actual films 90% of theoretically predicted isothermal films) is obtained. Experimental results show that a more drastic thermal reduction factor (as high as 50% for certain tests) is required.

Another source of descrepancy between calculated and measured film thickness using contact conductivity is the film constriction at the exit of the contact (Kannel (15), Schoeler (10)). It is known that at this constriction, film thickness can be lower than the uniform film thickness by 20% or more. Contact occurrences are apt to be generated in the constriction (even though it is short in the rolling direction) at a rate exceeding that predicted from the uniform film thickness. Detailed calculations and measurements of constriction shapes and a complex statistical analysis will be required to compute the quantitative effect of the constriction on contact conductivity results. At this time it can only be stated that the results will yield a film thickness between the constriction value and the uniform value.

In film measuring work conducted for another sponsor and reported in (10), tests were run using 6309 size bearings in SKF owned AR-2 test machines at 210°F, 4280 lbs. radial load, and 9700 rpm with polybutene oils. Film measurements were made using only the capacitive method, described in Section III of this report. In these tests, measured films were in much closer agreement with theoretically predicted (isothermal) values than in the present 7205 size bearing tests. Measured films were approximately 80% of the predicted values. That such good agreement exists in the 6309 size bearing tests is attributed to the fact that thermal effects are much less in these lower speed tests resulting in a smaller thermal reduction factor between measured and theoretical films.

It can be seen, that thermal effects and other causes justify doubt about theoretical film thickness predictions. Therefore a film measuring system capable of continuous film monitoring is a valuable and necessary means of evaluating the performance of various bearing-lubricant combinations over a wide range of test conditions.

An illustration of the usefulness of the system is given in the photographs in Enclosures 22, 23 and 27 which show the existence of contact occurrences as detected by the measuring system, where the isothermal theory suggests there should be no contacts. Post test bearing inspection revealed surface distress on the bearings which is a very good indication that partial EHD lubrication did exist and asperity interaction was indeed occurring. (For explanation of the causes of surface distress in these bearings the reader is referred to a discussion of bearing failure modes in reference 7.)

VII CONCLUSIONS

1. Electrical capacitance and conductivity instrumentation and techniques have been developed for the quantitative measurement of the lubricant film thickness in complete ball bearings. These methods are capable of being used at high speeds (43,000 rpm) and high temperatures (700°F).

2. The electrical characteristics of bearing lubricant films detected from capacitance and conductivity measurements can be interpreted to describe the nature of the films formed at bearing ball-race contacts over a wide range of operating conditions.

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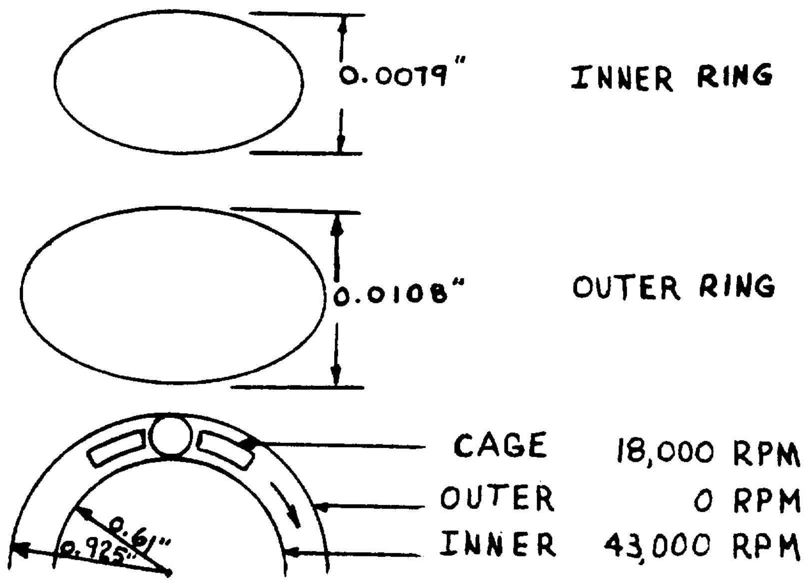
APPENDIX I

APPENDIX I

Determination of the Maximun Time of Traverse of a Single Contact Occurrence in a 7205 VAP Bearing at 43,000 rpm and 459 lbs. load



(INNER)

$$43{,}000 \text{ RPM} - 18{,}000 \text{ RPM} = 25{,}000 \text{ RPM}$$

$$\text{VELOCITY} = 25{,}000 \text{ RPM} \times \frac{1 \text{ MIN.}}{60 \text{ SEC.}} \times 2\pi(0.61) \frac{\text{IN.}}{\text{REV.}} = 1590 \frac{\text{IN.}}{\text{SEC.}}$$

MAX. TIME OF TRAVERSE THROUGH A HERTZ CONTACT

$$= \frac{0.0079 \text{ IN.}}{1590 \frac{\text{IN.}}{\text{SEC.}}} = 4.95 \times 10^{-6} \text{ SEC.} = 4.95\ \mu \text{ SEC.}$$

(OUTER)

$$\text{VELOCITY} = 18{,}000 \text{ RPM} \times \frac{1 \text{ MIN.}}{60 \text{ SEC.}} \times 2\pi(0.925) \frac{\text{IN.}}{\text{REV.}} = 1740 \frac{\text{IN.}}{\text{SEC.}}$$

MAX. TIME OF TRAVERSE

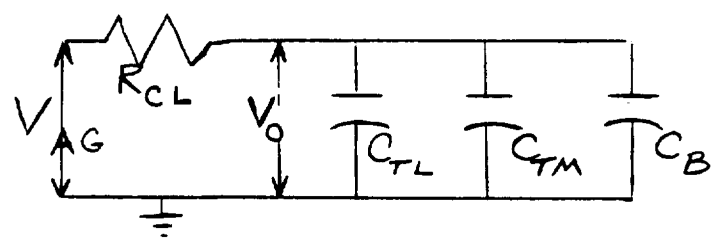
$$= \frac{0.0108 \text{ IN.}}{1740 \frac{\text{IN}}{\text{SEC.}}} = 6.2 \times 10^{-6} \text{ SEC.} = 6.2\ \mu \text{ SEC.}$$

APPENDIX II

DETERMINATION OF THE EFFECT OF CAPACITIVE LOADING ON CONTACT CONDUCTIVITY CIRCUITRY FOR FILM THICKNESS DETERMINATION

I. INTRODUCTION

When a bearing is operating under full EHD lubricant film conditions, the conductivity circuit, discussed in Section II of the text, consists of the configuration shown below:



where R_{CL} = current limiting resistance.

C_{TL} = capacitance of all test leads.

C_{TM} = capacitance of test machine.

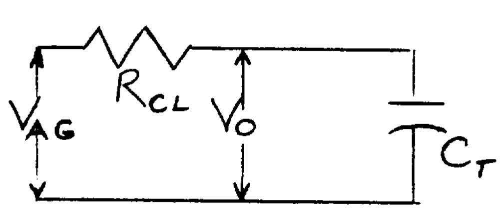
C_B = capacitance of bearing.

V_{AG} = output voltage from Audio Oscillator.

V_O = voltage across bearing.

Test conditions (high bearing surface roughness, thin lubricant films) may preclude the attainment of full EHD films in a given test. Under these conditions Vo, being immeasurable, must be calculated. The calculation proceeds as follows: The capacitive reactance Xct, of the equivalent series circuit shown below is given in equation 1.

$$X_{C_T} = \frac{1}{j\omega C_T} \qquad 1.$$



where X_{C_T} = capacitive reactance of C_T

C_T = combined capacitance of test bearing, C_B, the test rig, C_{TM}, and the test leads, C_{TL}.

ω = $(2\pi f)$ where f equals the frequency of the applied voltage V_{AG} and where ω, in vectorial notation, indicates the 90° phase shift associated with capacitive circuits, driven by a sinusoidal forcing function.

Current in the circuit is given by equation 2:

$$i = V_{AG} / Z \qquad 2.$$

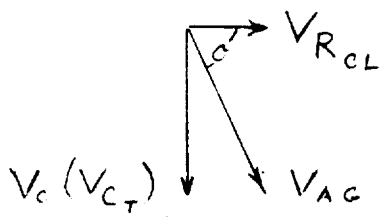
where Z is the total impedance of the series circuit given by equation 3:

$$Z = \sqrt{R_{CL}^2 + X_{C_T}^2} \qquad 3.$$

The tangent of the phase angle θ between the voltage across R_{CL}, and the applied voltage, V_{AG} is given by equation 4:

$$\tan \theta = X_{C_T} / R_{CL} \qquad 4.$$

The voltage relationships for the circuit are shown vectorially below:



The magnitude of V_O is given by equation 5:

$$V_O = V_{C_T} = i\,X_{C_T} = V_{AG}\,X_{C_T} / \sqrt{R_{CL}^2 + X_{C_T}^2} \qquad 5.$$

Since V_{AG}, R_{CL}, and w are known, and C_B is measurable, (by the capacitance technique described in Section III), the effect of capacitive loading on the system is determined.

II. APPLICATION

The presentation above is general. The conductivity system considered in Section II of this report, however, has imposed on it several constraints, the most pertinent of which, (to the subject discussion), is the upper bound of current limiting resistance (50 kilohms). Using a value of test lead capacitance of 350 pf, (i.e. a 25 foot length of, Belden RG58, low capacitance cable at 11 pf/ft.), a value of test rig capacitance of 80 pf (as empirically determined by a technique outlined in Section III C), and a bearing capacitance of 350 pf, (determined in Section III), for a nominal frequency of 500 Hz, and an applied voltage of 200 mv peak-peak, equations 1 through 5 yield the following:

$$X_{C_T} = \frac{1}{2(3.14)(500)(800\times10^{-12})} = 39.8\times10^{4}\,\Omega; \quad Z = \sqrt{(50\times10^{3})^2+(39.8\times10^{4})^2} = 4.01\times10^{5}\,\Omega$$

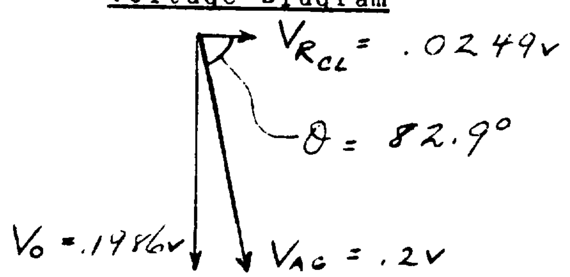
$$i = 0.2/4.01\times10^{5} = 49.9\times10^{-8}\,a; \quad \theta = \tan^{-1}\left(39.8\times10^{4}/50\times10^{3}\right) = 82.9^{\circ}$$

$$V_{R_{CL}} = (49.9\times10^{-8})(50\times10^{3}) = 24.9\times10^{-3}\,v$$

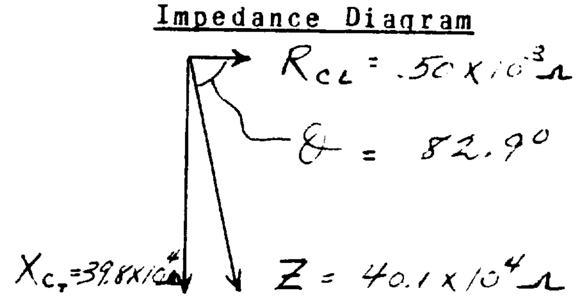
$$V_{X_{C_T}} = V_o = (39.8)(10^{4})(49.9)(10^{-8}) = .1986\,v$$

The circuit is represented vectorially below:

Voltage Diagram



Impedance Diagram



It is apparent, that for the conductivity test parameters described above, the simplest case, where the full film voltage nearly equals the applied voltage (within 1 %), is obtained.

For these and similar operating parameters, (i.e. when $R_{CL} \ll X_{CT}$) V_o may be considered equal to V_{AG}. Recalculation must be performed whenever system parameters, such as bearing capacitance, current limiting resistance, or operating frequency, are significantly increased.

APPENDIX III

APPENDIX III

Determination of the No Contact Time Fraction for a 7205 Bearing

The value of T/To required for calculation of the film parameter h/σ refers to the fraction of time that no asperity contact exists between one pair of bodies forming a single Hertz contact.

If in conductivity testing the voltage is recorded across a set of two bearing rings with twelve equally loaded balls interposed, the value of T/To measured will be the percentage of time that none of the twelve balls simultaneously contacts both rings.

Section 1

No Contact Time Fraction for a Sample Elliptical Contact

The probability T/To that no contact exists in a sample contact between the asperities on two surfaces separated by an oil film of thickness h is shown in (14) to be expressible as,

$$T/T_o = [1-f]\,\frac{T_1}{T_o}(\xi) \qquad 1.$$

where ξ = ratio of film thickness h to composite surface roughness σ

$\frac{T_1}{T_o}(\xi)$ = cumulative distribution function of the asperity amplitudes of the composite surface,

and f is the following integral evaluated over the nominal surface contact area

$$f = \int_A e^{-(x^2+y^2)^{1/2}/\bar{r}_\xi}\, dx\, dy \qquad 2.$$

where

$\bar{r}_\xi$ = one half the average distance between the downward and a subsequent upward crossing at the level $\lambda = \xi\sigma$ above the centerline of the composite surface roughness process.

For an elliptical contact area with respective semimajor and semiminor axes a and b, f may be expressed as follows:

$$f = \frac{4}{\pi}\int_0^{a/\bar{r}_\xi}\int_0^{a/b\bar{r}_\xi\sqrt{b^2-(Y\bar{r}_\xi)^2}} \exp\{-(X^2+Y^2)\}\, dX\, dY \qquad 3.$$

when $X = x/\bar{r}_\xi$ and $Y = y/\bar{r}_\xi$

A digital computer program was written to perform the integration of Eq 3 numerically by means of Weddle's rule (16) and evaluate Equation 1 using the values of the function $T_1/To(\xi)$ published in ref. (2). The inputs to the program are contact ellipse dimensions a and b. These dimensions vary with bearing design, thrust load and speed among other things and were arrived at here using a high speed ball bearing computer program described in (7).

The results of the computation program are given in Table AIII/1 at the end of this appendix for a 7205 bearing operating at a speed of 43,000 rpm at thrust loads of 200 lbs. and 459 lbs. Since ellipse dimensions are different for inner and outer rings, results are given for both contacts. The following section takes this difference into account.

Section 2

No Contact Time Fraction as Measured Across Bearing Rings

Each of the balls in a thrust loaded ball bearing provides a parallel path through which current can flow between inner and outer rings. For a 7205 bearing, the ellipses of contact with the outer ring are of different size than the inner ring contact ellipses.

Thus a relation $(T/To[\xi])_I$ will exist for the inner ring contacts and a different relation $(T/To[\xi])_o$ will exist for the outer ring contacts. This is, for a given film thickness assumed equal at both inner and outer contacts and surface roughnesses (and hence σ value) assumed equal at both inner and outer rings, the no-contact time fraction will differ because of the difference in contact dimensions.

For fixed ξ the probability that any one ball provides a conducting path is the product of the probabilities that both contacts of the ball conduct is,

$$P_{rob}[\text{Ball conducts}] = [1-(T/T_o)_I][1-(T/T_o)_o] \qquad 4.$$

The probability that a ball does not conduct is the complement, i.e.

$$P_{rob}[\text{Ball does not conduct}] = 1-[1-(T/T_o)_I][1-(T/T_o)_o] \qquad 5.$$

The probability that no ball conducts assuming independence of the balls is the product of the individual probabilities of each ball not conducting. On the other hand the probability that no ball conducts is the probability that no contact takes place across the two bearing rings i.e., it equals $(T/To)_{rings}$.

Thus for a thrust loaded 7205 bearing with 12 balls one has

$$(T/T_o)_{rings} = \left\{ 1 - [1 - (T/T_o)_o][1 - (T/T_o)_I] \right\}^{12} \qquad 6.$$

The solution of the equation 6 is arrived at by inserting into it the individual T/To values for inner and outer ring contact for given h/σ values (obtained from Section 1 of this Appendix) and solving for T/To (across rings). The desired relation of T/To (across rings) vs. h/σ may then be plotted. The solutions of the above equation are tabulated in Table AIII/1 along with the input data from Section 1 of this Appendix. The plots of T/To (across rings) vs. h/σ are given in Enclosure 13 of the report.

TABLE AIII/1

Speed (rpm) Load (lbs.)	43,000 459			43,000 300		
Contact Ellipse	Inner	Outer		Inner	Outer	
a. X10^4 μ in.	3.351	3.664		2.886	3.342	
b. X10^4 μ in.	0.395	0.540		0.341	0.494	
h/σ Value	T/To Inner	T/To Outer	T/To Across Rings	T/To Inner	T/To Outer	T/To Across Rings
4.0			0.984*			0.988*
3.8			0.967*			0.976*
3.6			0.940*			0.957*
3.4	0.9203	0.8893	0.8994	0.9352	0.9023	0.9266
3.2	0.8978	0.8589	0.8400	0.9163	0.8747	0.8812
3.0	0.8506	0.7964	0.6903	0.8758	0.8172	0.7591
2.8	0.8256	0.7645	0.6043	0.8538	0.7874	0.6846
2.6	0.8009	0.7332	0.5194	0.8318	0.7579	0.6189
2.4	0.7310	0.6463	0.3012	0.7688	0.6755	0.4500
2.2	0.6698	0.5725	0.1610	0.7128	0.6045	0.2353
2.0	0.5615	0.4475	0.0358	0.6121	0.4827	0.0680
1.8	0.4647	0.3439	0.0056	0.5198	0.3795	0.0143
1.6	0.3168	0.2014	0.0000	0.3740	0.2331	0.0004
1.4	0.1820	0.0928	-	0.2322	0.1153	0.0000
1.2	0.0875	0.0335	-	0.1240	0.0455	-
1.0	0.0295	0.0075	-	0.0486	0.0115	-

* Extrapolated Values

APPENDIX IV

APPENDIX IV

PROPERTIES OF PARTS MADE FROM SP-1 RESIN

I. Mechanical Properties

Tensile Strength

600°F (315°C) 5,000 psi

720°F (400°C) 3,500 psi

Shear Strength

73°F (23°C) 11,900 psi

Compressive Strength

24,400 psi

II Thermal Properties

Coefficient of Linear Thermal Expansion

Range, °F	Coefficient, microinches/in./°F
73° -752°	35.4

Thermal Conductivity

2.20 BTU/hr.ft.^{2} °F in.

Specific Heat (D648)

0.27 BTU/lb. °F

Chemical Resistance

Insoluble in organic solvents. Sensitive to strong bases, (e.g., flex. mod. decreases by 50% after 100 hours in 10% sodium hydroxide). Much less sensitive to strong acids.

Flammability

Non-burning. Decomposes slowly without visible burning in propane flame.

Hardness

83-89 Rockwell H 112 Rockwell M

Specific Gravity

1.41 - 1.43

Color

Dark Brown to Black

APPENDIX V

APPENDIX V

DETERMINATION OF FILM THICKNESS FROM CAPACITANCE MEASUREMENTS

In order to estimate the film thickness in the contacts of this angular contact ball bearing (7205 VAP) under axial loading, the capacitance technique outlined by Dyson, etc. (9) is used. Since the relations developed in (9) are for lubricated cylinders, the following assumptions are made in applying these relations to ball bearings:

1) Film thicknesses between ball and outer race and between ball and inner race are equal.*

2) Surfaces in Hertzian contact area are parallel planes.

3) Inlet and both sides (in plane perpendicular to rolling direction) of the ball are filled with oil out to distances from the contact at which the capacitance is negligible.

4) Outlet region is filled with both oil and air in a proportion according to (9).

With these assumptions, the capacitance, across any one contact can be written as:

$$C = C_1 + C_H + C_2 + C_L \qquad 1.$$

where C_1 = capacitance across the surfaces in inlet region.

C_H = capacitance across Hertzian contact.

C_2 = capacitance across the surfaces in outlet region.

* Extensive computations (not given here) show that the film thicknesses at the inner ring and outer ring contacts differ only by about 5%.

C_L = capacitance across groove surface in plane perpendicular to rolling direction. Using the subscripts IR and OR for inner and outer ring contacts respectively the capacitance in these two contacts can be given in the following two equations:

$$C_{iR} = C_{1i} + C_{Hi} + C_{2i} + C_{Li} \qquad 2$$

$$C_{OR} = C_{1O} + C_{HO} + C_{2O} + C_{LO} \qquad 3$$

Therefore, the capacitance, C_T, between inner and outer ring is:

$$C_T = Z \left[\frac{(C_{iR})(C_{OR})}{C_{iR} + C_{OR}} \right]$$

where Z = number of balls in bearing.

The eight different capacitances entered in Equation 2 and 3 are individually determined for each film thickness using the relations given in (9). Here, in the place of roller length, minor and major axes of the Hertzian contact ellipse are used in determining inlet and side capacitances respectively.

Subscripts

i refers to inner

o refers to outer

1 refers to inlet which is full of oil

2 refers to outlet which is filled with oil and air

L refers to one side in the plane perpendicular to the direction of rolling

CAPACITANCE CALCULATIONS

DATA

Load = 459 lbs.

Speed = 43,000 rpm, 12 balls

Ball Diameter = 5/16"; ball radius = 5/32" = .1561"

Groove radius = 0.166" = r_g

Inner Ring Track Radius = r_i = 0.653"

Outer Ring Track Radius = r_o = 0.965"

Dielectric Constant of Oil = ϵ_o = 2.0

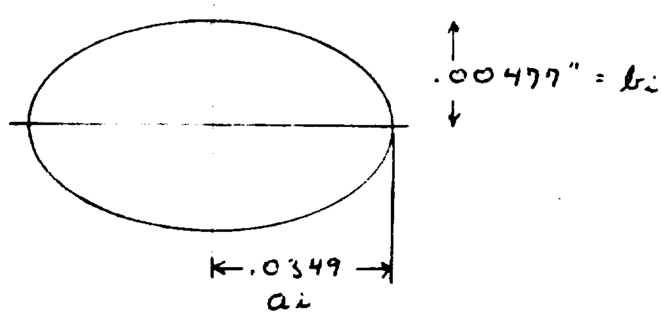
Oil Film Thickness = ho

CONTACT AREA DIMENSIONS

Inner Ring Contact

$A_i = \pi a_i b_i$

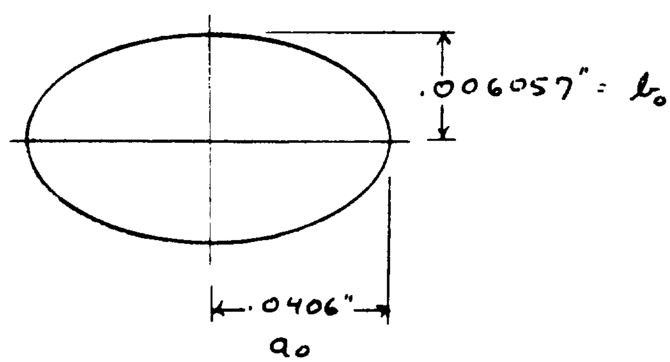
$= 5.24 \times 10^{-4}\ \text{IN}^2$



Outer Ring Contact

$A_o = \pi a_o b_o$

$= 7.74 \times 10^{-4}\ \text{IN}^2$



Capacitance At Inner Race

$$C_{iR} = C_{Hi} + \underset{\text{INLET}}{C_{1i}} + \underset{\text{OUTLET}}{C_{2i}} + \underset{\text{SIDES}}{C_{Li}}$$

Capacitance At Outer Race

$$C_{OR} = C_{HO} + C_{1O} + C_{2O} + C_{LO}$$

where

$$C_{Hi} = \frac{\epsilon_o A_i}{4\pi h_o}\left(\frac{2.54}{0.9}\right) \text{ PICOFARADS}$$

$$C_{HO} = \frac{\epsilon_o A_o}{4\pi h_o}\left(\frac{2.54}{0.9}\right)$$

$$C_{1i} = (2a_i)\,Y_{1i}\,\epsilon_o\sqrt{\frac{R_i}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$C_{1O} = (2a_o)\,Y_{1O}\,\epsilon_o\sqrt{\frac{R_O}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$C_{2i} = (2a_i)\,Y_{2i}\sqrt{\frac{R_i\,\epsilon_o}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$C_{2O} = (2a_o)\,Y_{2O}\sqrt{\frac{R_O\,\epsilon_o}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$C_{Li} = (2b_i)\,Y_{Li}\,\epsilon_o\sqrt{\frac{R_L}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$C_{LO} = (2b_o)\,Y_{LO}\,\epsilon_o\sqrt{\frac{R_L}{h_o}}\left(\frac{2.54}{0.9}\right)$$

$$R_i = \frac{\gamma_b \times \gamma_i}{\gamma_b + \gamma_i}$$

$$R_O = \frac{\gamma_b \times \gamma_o}{\gamma_b + \gamma_o}$$

$$R_L = \frac{\gamma_b \times \gamma_g}{\gamma_b + \gamma_g}$$

(γ_g IS SAME FOR INNER AND OUTER)

NUMERICAL CALCULATIONS

$$C_{Hi} = \frac{2.0 \times 5.24 \times 10^{-4} \times 2.82}{4 \pi h_o}$$

IF $h_o = 7.1 \times 10^{-6}$ IN.

$$C_{Hi} = \underline{\underline{33.1 \text{ PF}}}$$

$$C_{Ho} = \underline{\underline{48.9 \text{ PF}}}$$

$$R_L = \frac{0.1561(-0.166)}{-0.01} = 2.59 \text{ IN}$$

$$R_i = \frac{0.1561(0.653)}{0.8091} = 0.126 \text{ IN.}$$

$$R_o = \frac{0.1561(-0.965)}{-0.809} = 0.1863 \text{ IN}$$

$$X_{1i} = \frac{(4.77 \times 10^{-3})^2}{2(0.126)h_o} = 12.75$$

$$X_{2i} = \frac{2(4.77 \times 10^{-3})^2}{2(0.126)h_o} = 25.50$$

$$X_{1o} = \frac{(6.057 \times 10^{-3})^2}{2(0.1863)h_o} = 13.84$$

$$X_{2o} = \frac{2(6.057 \times 10^{-3})^2}{2(0.1863)h_o} = 27.68$$

$$X_{Li} = \frac{(3.49 \times 10^{-2})^2}{2(2.59)h_o} = 33.2$$

$$X_{Lo} = \frac{(4.06 \times 10^{-2})^2}{2(2.59)h_o} = 44.8$$

Y's are obtained from the Table given in (9) using X's given below:

$$\left.\begin{aligned} X_{1i} &= \frac{b_i^2}{2 R_i \lambda_o} \\ X_{1o} &= \frac{b_o^2}{2 R_o \lambda_o} \end{aligned}\right\} \text{INLET}$$

$$\left.\begin{aligned} X_{2i} &= \frac{\epsilon_o b_i^2}{2 R_i \lambda_o} \\ X_{2o} &= \frac{\epsilon_o b_o^2}{2 R_o \lambda_o} \end{aligned}\right\} \text{OUTLET}$$

$$\left.\begin{aligned} X_{Li} &= \frac{a_i^2}{2 R_L \lambda_o} \\ X_{Lo} &= \frac{a_o^2}{2 R_L \lambda_o} \end{aligned}\right\} \text{SIDES}$$

$Y_{1i} = 0.1016$ $\qquad$ $Y_{1o} = 0.1000$

$Y_{2i} = 0.0928$ $\qquad$ $Y_{2o} = 0.0915$

$Y_{Li} = 0.0595$ $\qquad$ $Y_{Lo} = 0.0859$

$\sqrt{R_i} = 0.355$ $\qquad$ $\sqrt{R_o} = 0.432$ $\qquad$ $\sqrt{R_L} = 1.61$

$$C_{1i} = 2(.0349)\,0.1016 \times 2 \times \frac{(0.355)(2.82)}{\sqrt{h_o}} = 5.34$$

$$C_{2i} = 2(.0349)\,0.0928 \times 1.414 \times \frac{(0.355)(2.82)}{\sqrt{h_o}} = 3.44$$

$$C_{Li} = 2(.00477)\,0.0595 \times 2 \times \frac{(1.61)(2.82)}{\sqrt{h_o}} = 2.91$$

$$C_{1o} = 2(.0406)\,0.1000 \times 2 \times \frac{(0.432)(2.82)}{\sqrt{h_o}} = 7.42$$

$$C_{2o} = 2(.0406)\,0.0915 \times 1.414 \times \frac{(0.432)(2.82)}{\sqrt{h_o}} = 4.82$$

$$C_{Lo} = 2(.00606)\,0.0859 \times 2 \times \frac{(1.61)(2.82)}{\sqrt{h_o}} = 3.55$$

THEN

$$C_{1i} + C_{2i} + C_{Li} = 5.34 + 3.44 + 2.91 = \underline{\underline{11.69}}$$

$$C_{2i} + C_{2o} + C_{Lo} = 7.42 + 4.82 + 3.55 = \underline{\underline{15.79}}$$

$$C_{iR} = 33.1 + 11.7 = 44.8 \text{ pF}$$

$$C_{oR} = 48.9 + 15.5 = 64.7 \text{ pF}$$

$$C_{BALL} = \frac{C_{iR} \times C_{oR}}{C_{iR} \times C_{oR}} = \frac{(44.8)(64.7)}{44.8 + 64.7} = 26.5 \text{ pF}$$

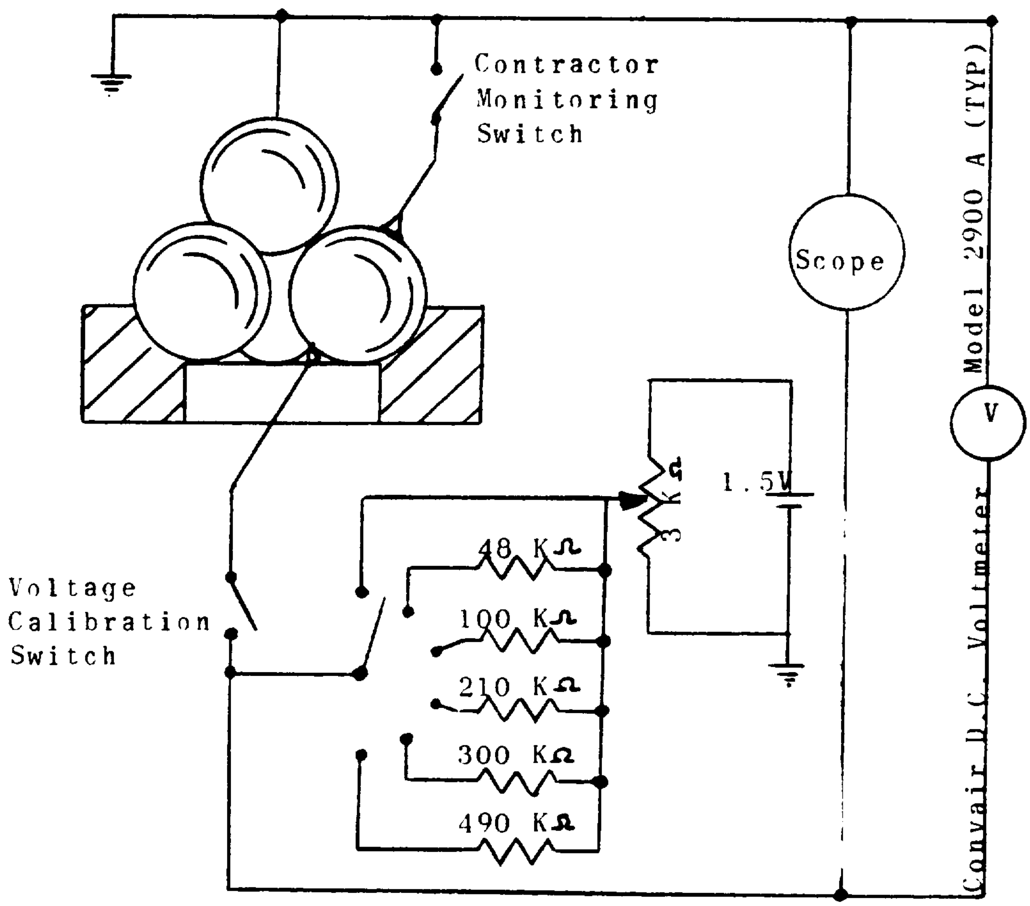
$$C_T = \Sigma C_B = 12 \times 26.5 = \underline{\underline{318 \text{ pF}}}$$

Enclosure 18 contains curves of capacitance vs. film thickness obtained using the above method.

Note: The curves given in Enclosure 18 were generated for a 7205 VAP bearing as used for the film measurements work reported here and in (13). In the sample calculations given above, geometric dimensions slightly different from those of the 7205 VAP bearing were used. Therefore, the data points arrived at in this Appendix may not directly coincide with the curves of Enclosure 18.

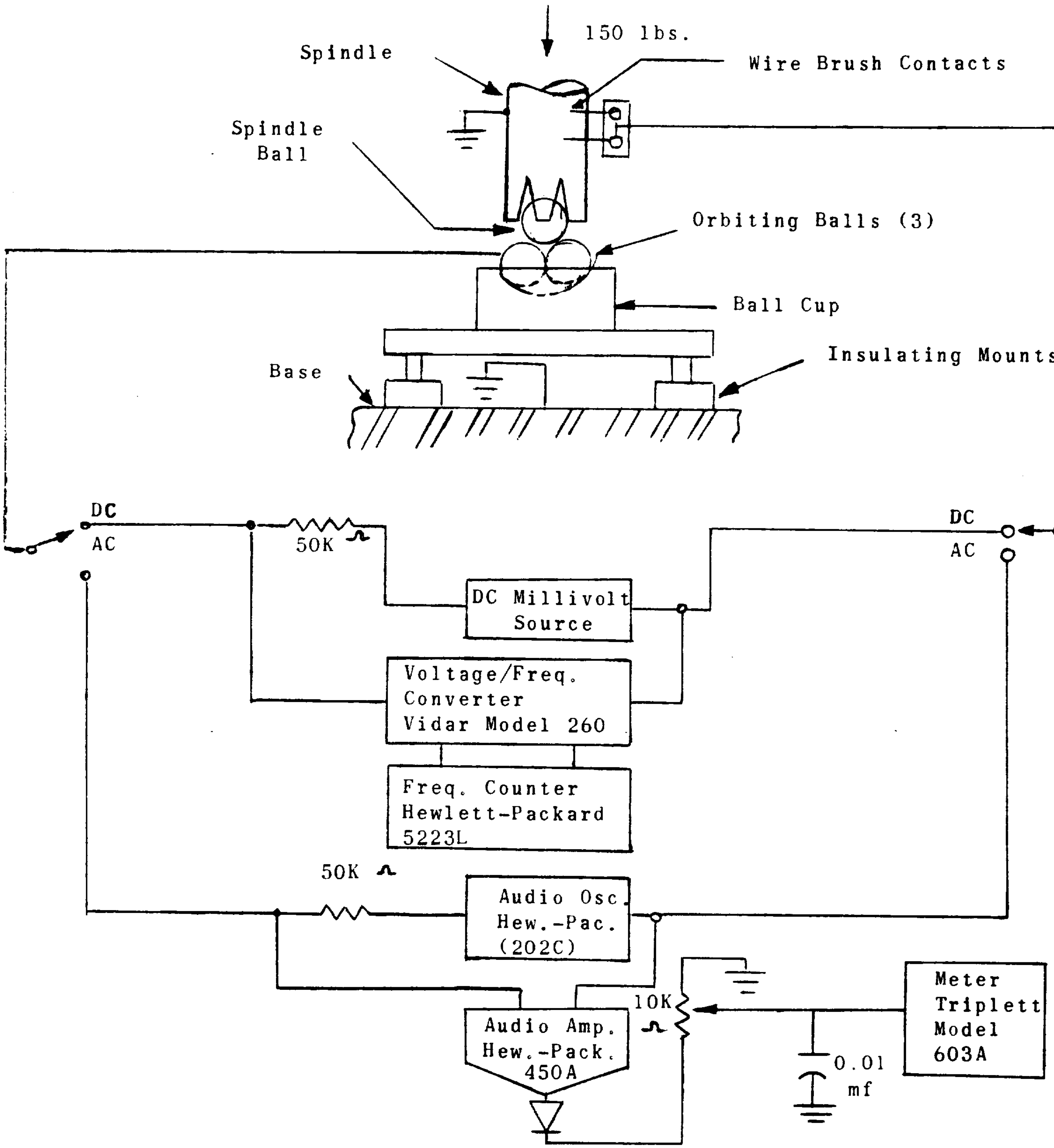
ENCLOSURE 1

ELECTRICAL CIRCUIT DIAGRAM OF THE FOUR-BALL TESTER



ENCLOSURE 2

BLOCK DIAGRAM OF APPARATUS USED IN CORRELATING DC AND AC CONDUCTIVITY TECHNIQUES IN THE FOUR-BALL TESTER



ENCLOSURE 3

FILM THICKNESS DATA OBTAINED FOR A SEQUENCE OF INCREASING SPEEDS IN BARWELL FOUR BALL TESTER

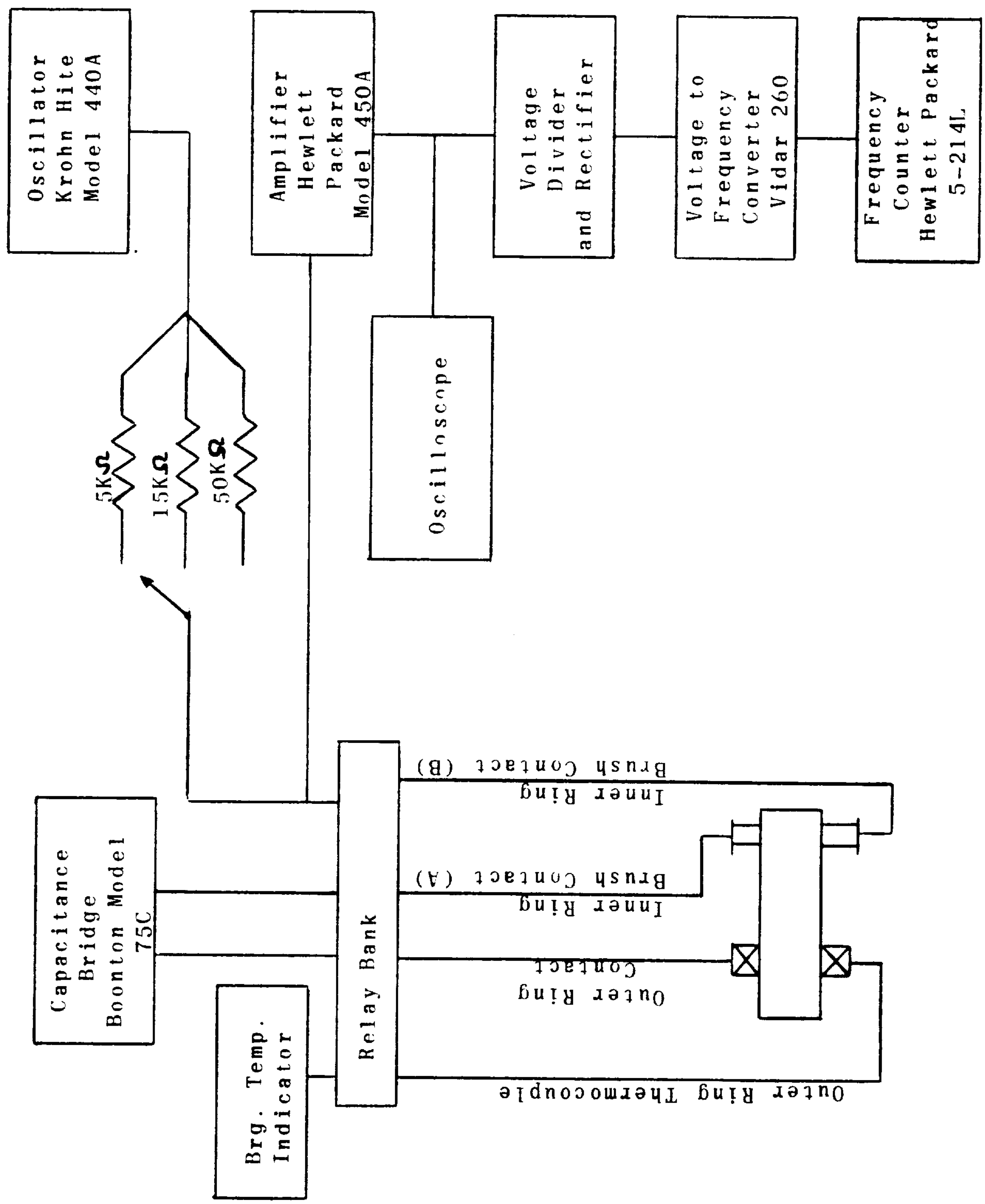
Maximum Hertzian Contact Stress - 640,000 psi

Spindle Speed (RPM)	V/Vo AC	V/Vo DC	Total System Capacitance (pf)
250	0	0	*
300	0	0	*
350	0.03	0.0923	*
400	0.18	0.15640	*
450	0.47	0.49733	*
500	0.87	0.77000	140.2
550	0.92	0.89753	128.1
600	0.84	0.83402	146.0
700	0.97	0.98436	120.7
800	0.98	0.99072	117.2
900	0.97	0.98074	114.5
1000	0.94	0.95556	112.9
1250	0.985	0.99985	107.1
1500	0.99	0.99908	104.4
2000	0.995	0.99981	101.6
2500	0.99	0.99663	98.7

* Not possible to obtain null indication on capacitance bridge.

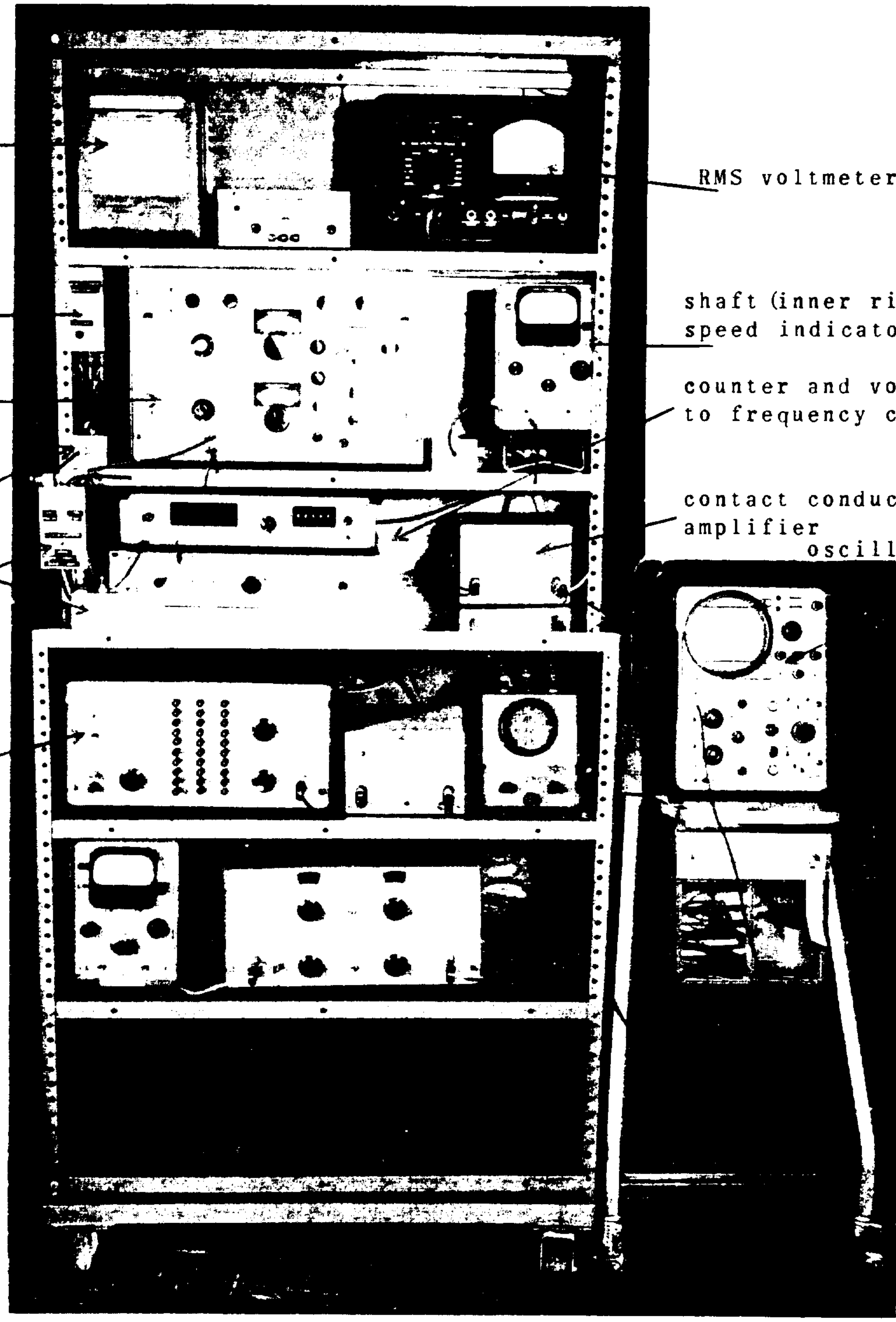
ENCLOSURE 4

BLOCK DIAGRAM OF INSTRUMENTATION USED FOR ACQUISITION OF FILM THICKNESS DATA



ENCLOSURE 5

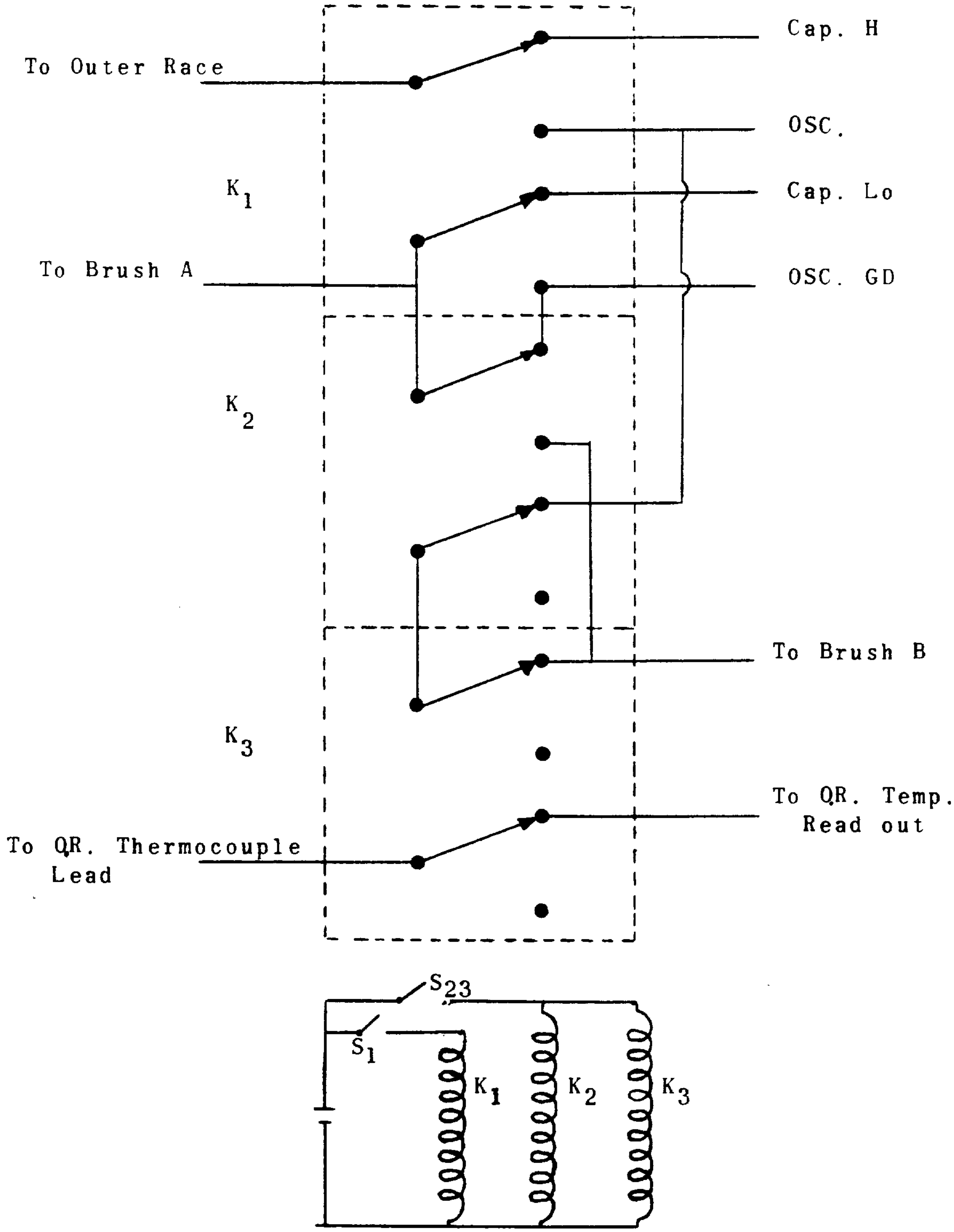
PHOTOGRAPH OF THE FILM MEASURING INSTRUMENTATION



Note: Additional instrumentation comprises cage speed measuring system discussed in (11).

ENCLOSURE 6A

RELAY SWITCHING CIRCUIT FOR ACQUISITION OF FILM THICKNESS DATA

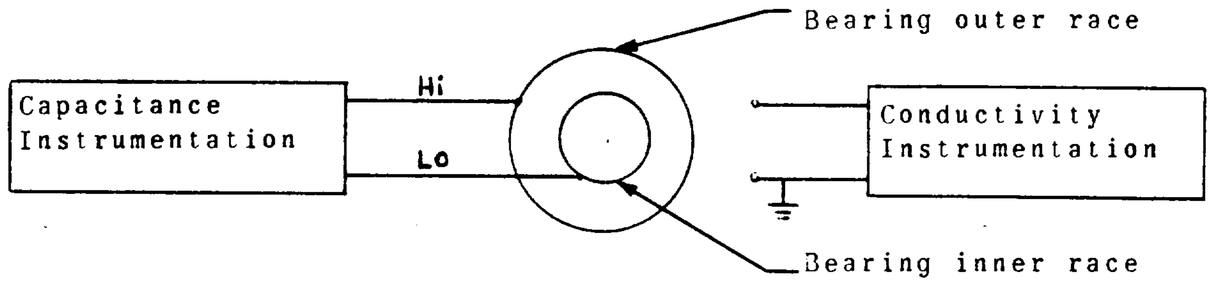


ENCLOSURE 6B

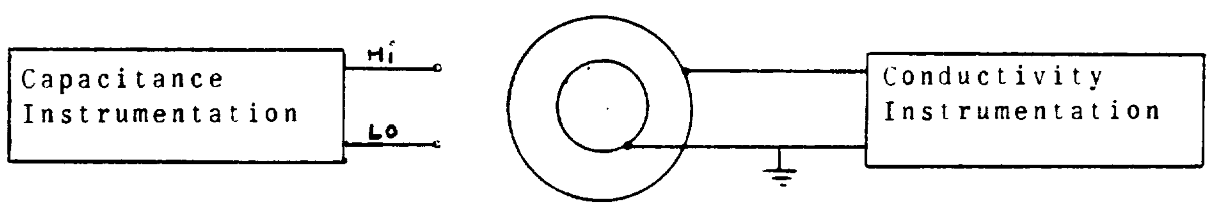
RELAY FUNCTION DIAGRAM

S_{23} Open: Permits operation of S_1

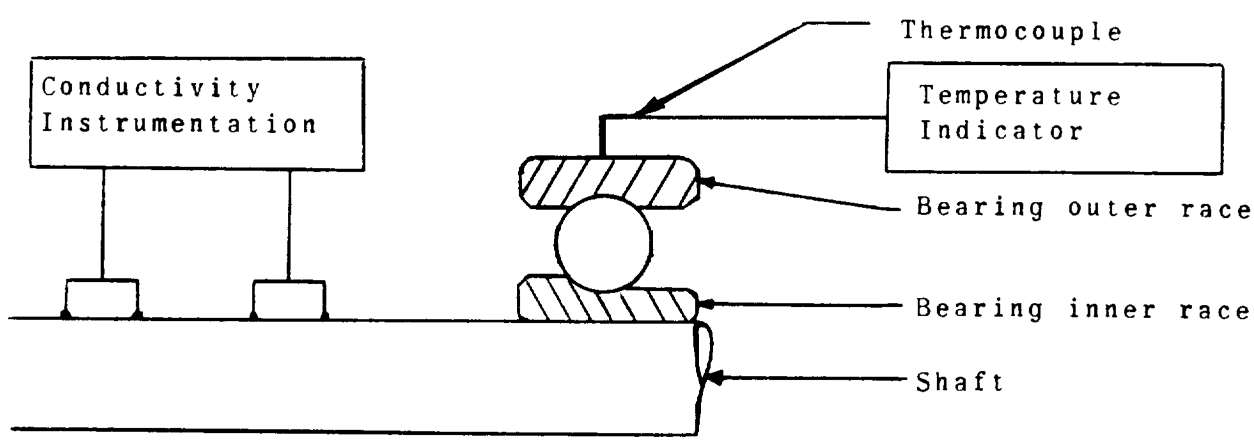
S_1 Open: Permits measurement of intrabearing capacitance.
: Permits checkout of conductivity measuring circuitry with bearing decoupled



S_1 Closed: Permits measurement of contact conductivity
Permits balance of capacitance bridge

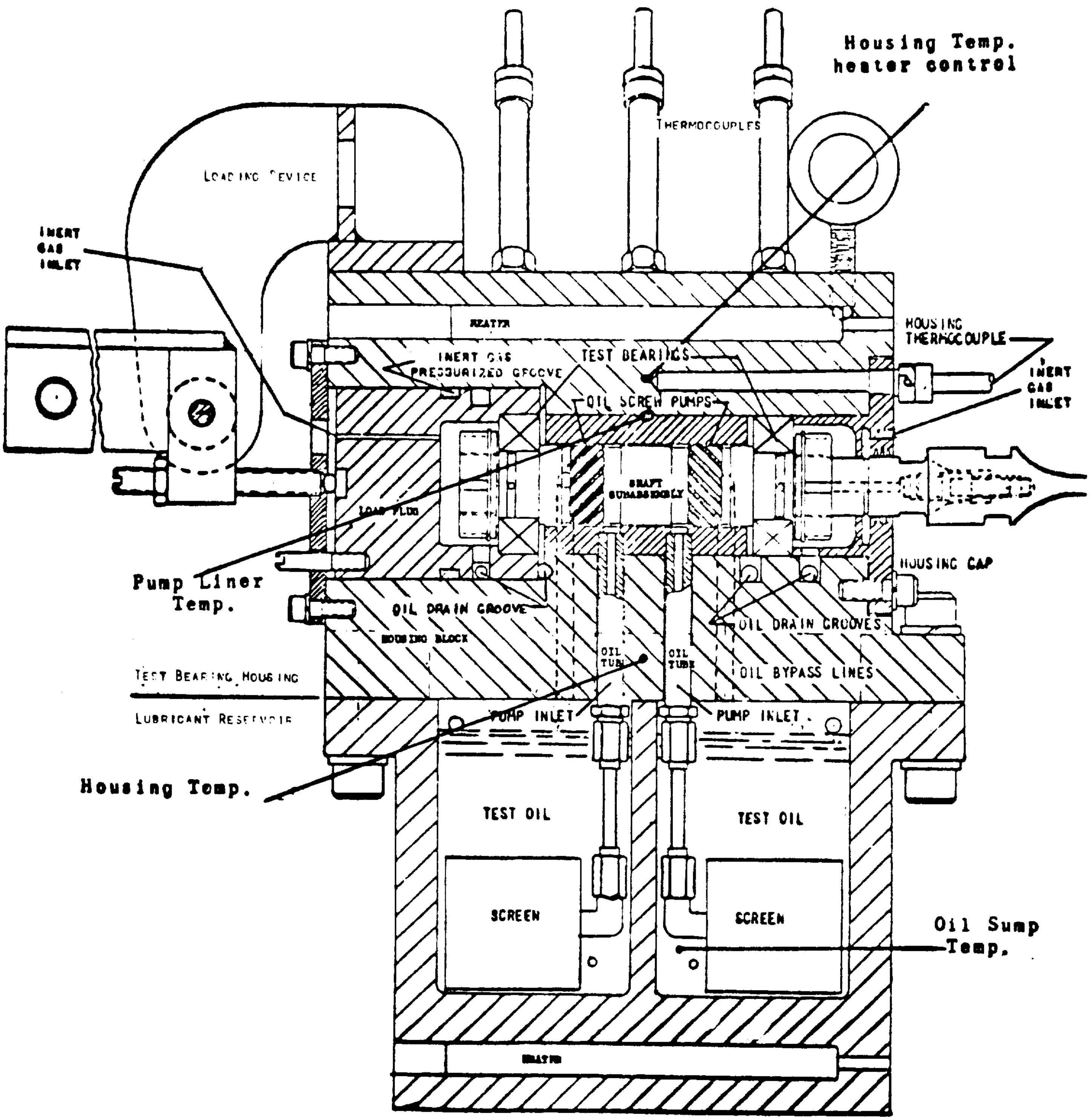


S_{23} Closed: Decouples bearing from film measuring instrumentation.
: Permits measurement of temperature of bearing outer race.
: Permits check of electrical conductivity of wire brush slip ring assembly.



ENCLOSURE 7

LAYOUT SKETCH OF HIGH-SPEED HIGH-TEMPERATURE TEST RIG



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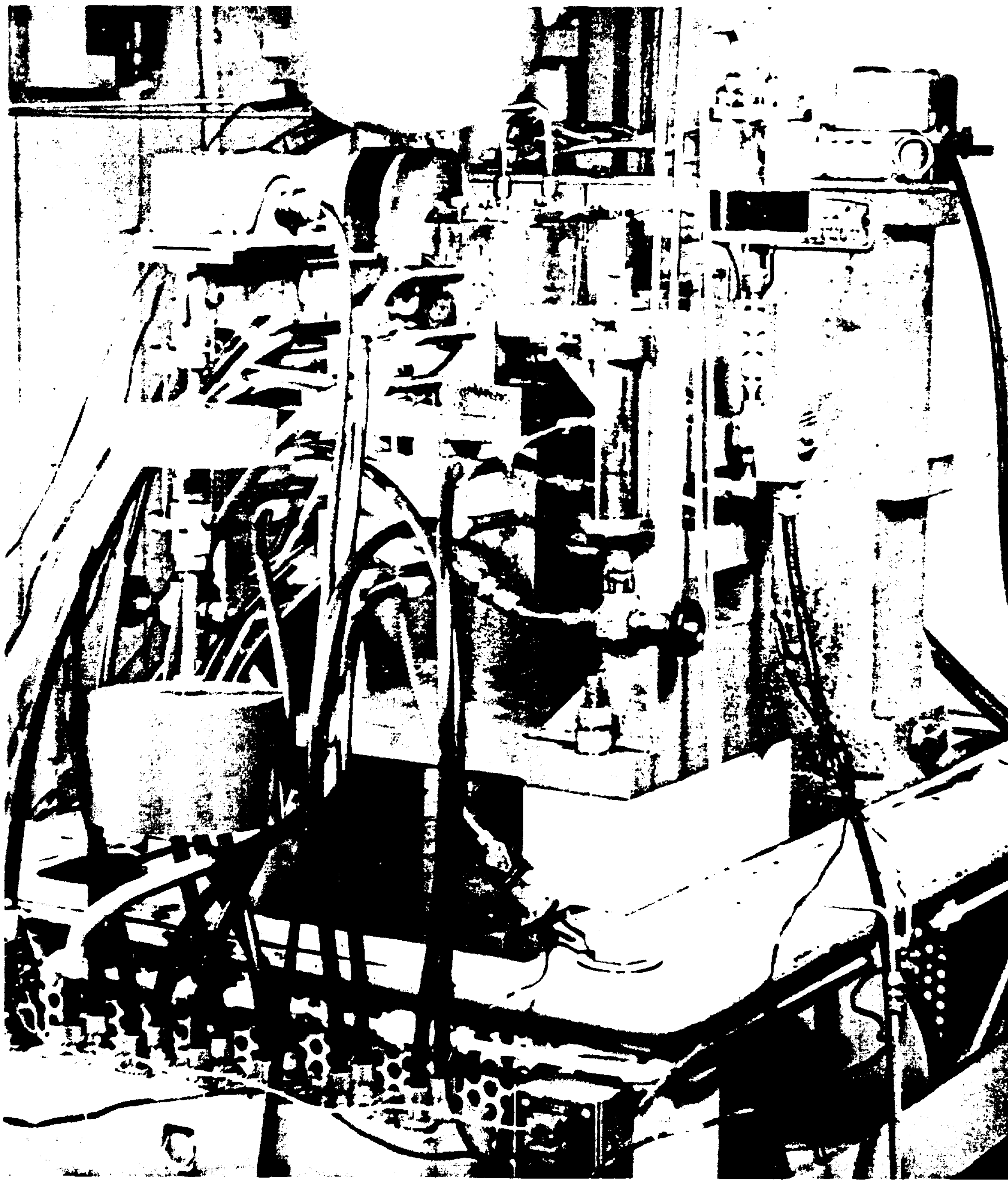
ENCLOSURE 8

HIGH-SPEED HIGH-TEMPERATURE BEARING TEST MACHINE



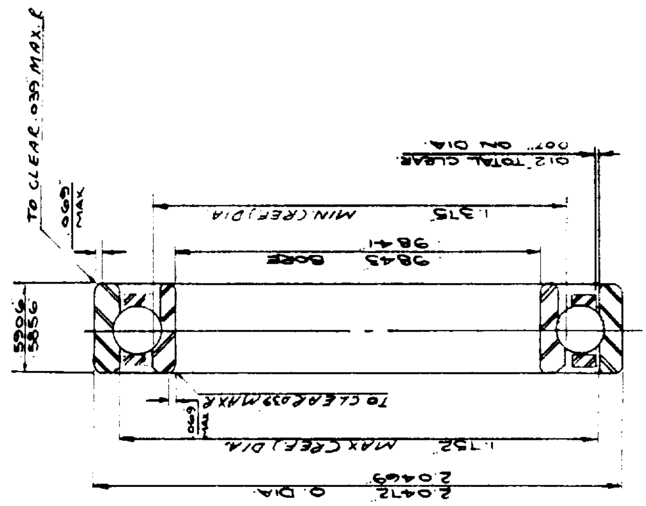
ENCLOSURE 9

7205 VAP TEST BEARING

7205 VAP

BEARING DATA	SKF
VENDOR'S PART №	7205 VAI
VENDOR'S DRAWING №	7205 VAI
BEARING TOLERANCE	ABEC5
№ & SIZE OF BALLS	12-.3175" DIA.
INTERNAL RADIAL LOOSENESS (TOTAL)	.0020"-.0024"
TYPE OF BEARING	ANGULAR CONTACT
DESIGN CONTACT ANGLE	24°
PITCH DIA. (NOMINAL)	1.541
CAGE WIDTH	.555

1. INNER AND OUTER RINGS TO BE MADE FROM M-50 STEEL, HARDNESS NOM. RC 62, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER-GRAFF INTERCEPT METHOD.
2. BALLS TO BE MADE FROM M-50 STEEL HARDNESS NOM. RC 62, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER-GRAFF INTERCEPT METHOD.
3. CAGE TO BE MADE FROM SILVER PLATED M-1 STEEL HARDNESS RC 55 MIN. ONE PIECE MACHINED, OUTER LAND RIDING.
4. GROOVE CONFORMITIES TO BE 52.3 % NOM. FOR INNER RING AND 52.3% NOM. FOR OUTER RING
5. SHOULDER HEIGHTS TO BE 24.8-26.2 % FOR THE INNER RING AND 16.5-16.9 % FOR THE OUTER RING.
6. CROSS GROOVE SURFACE ROUGHNESS TO BE 4 MICRO INCHES RMS MAX. FOR BOTH INNER AND OUTER RINGS. SURFACE ROUGHNESS TO BE 1.2 MICRO-INCHES RMS MAX. FOR THE BALLS.
7. INNER AND OUTER RINGS TO BE BLACK OXIDE COATED PER AMS 2485



SKF INDUSTRIES, INC. PHILADELPHIA, PA.

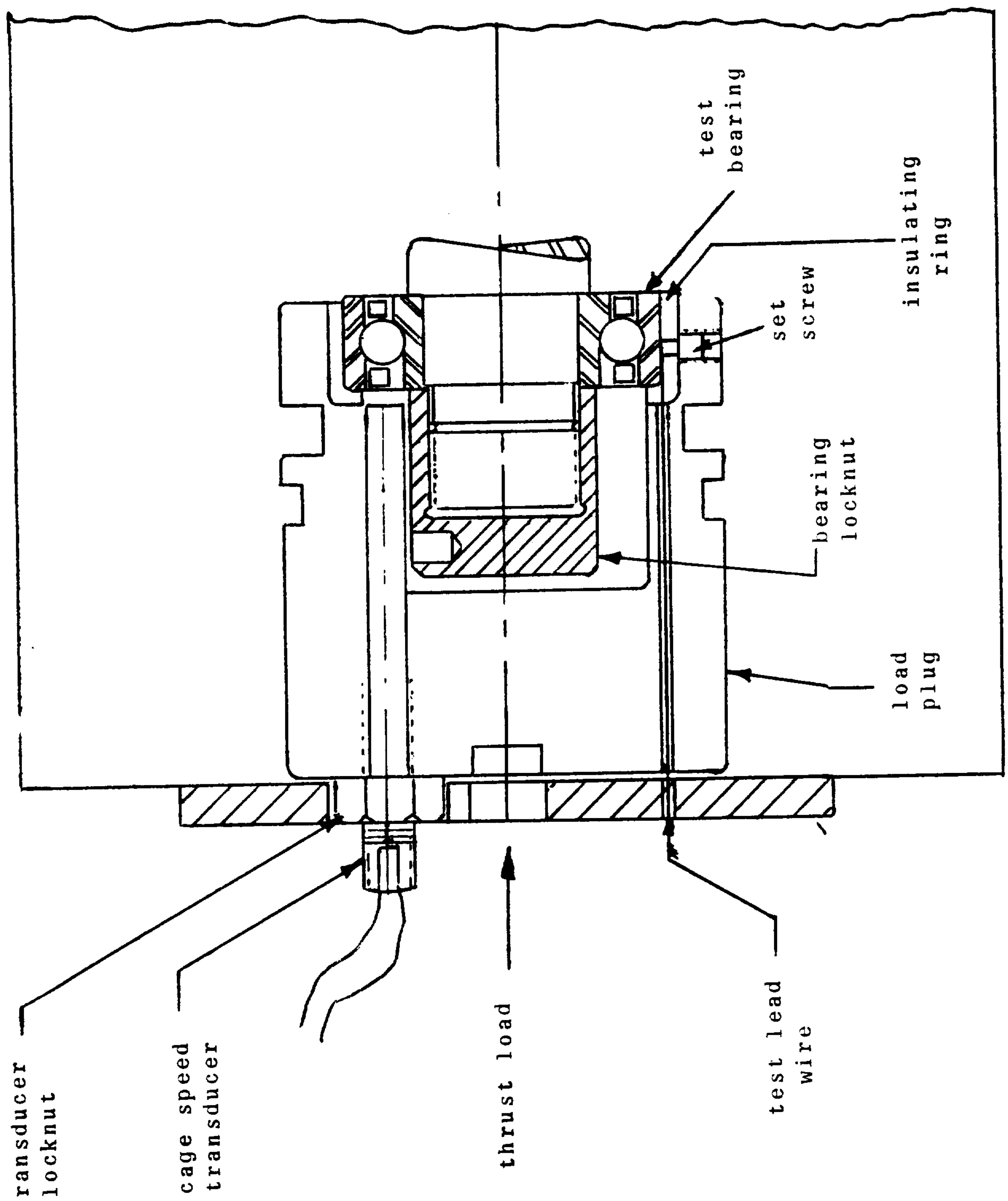
BRG № 7205 VAP

DRAWN	CHECK	APPR	REQ.
SCALE			DATE

7205 VAP

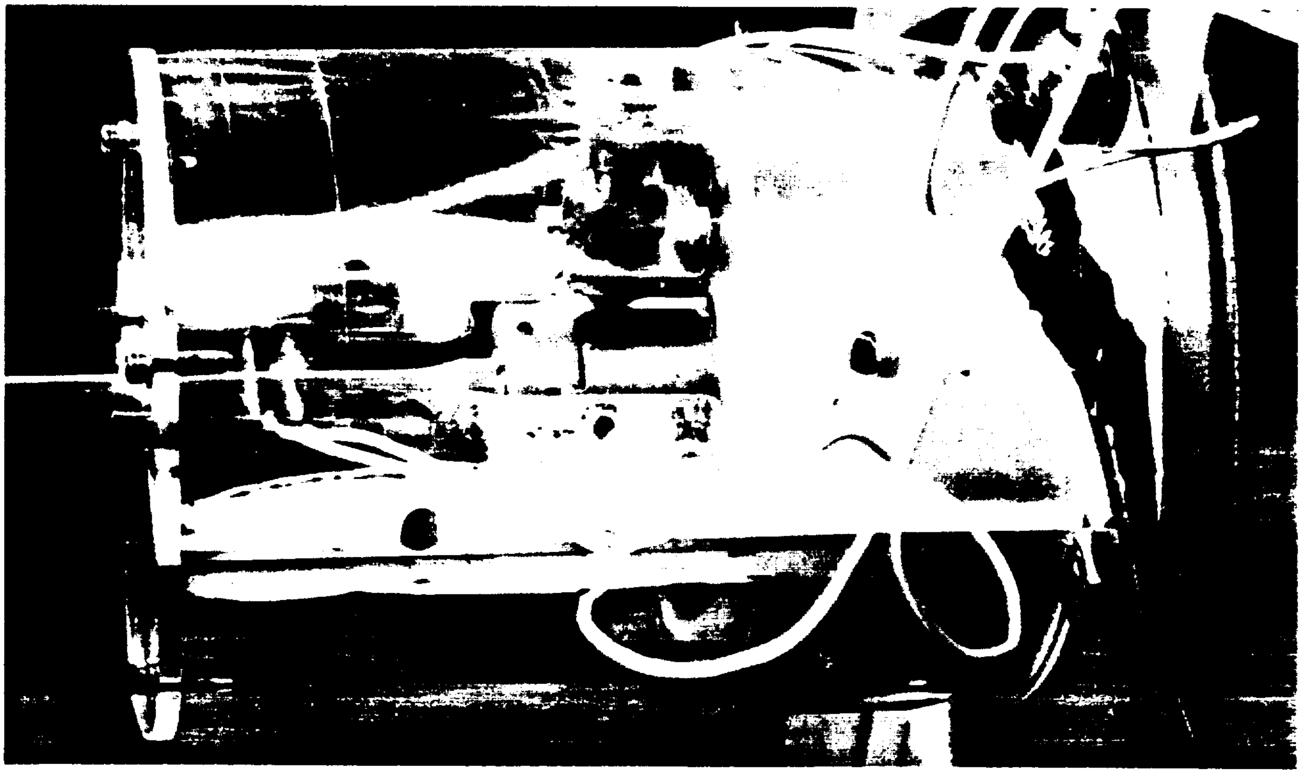
ENCLOSURE 10

SKETCH OF LOADING PLUG AND BEARING, POLYIMIDE INSULATING RING, AND CONNECTION TO INNER RING

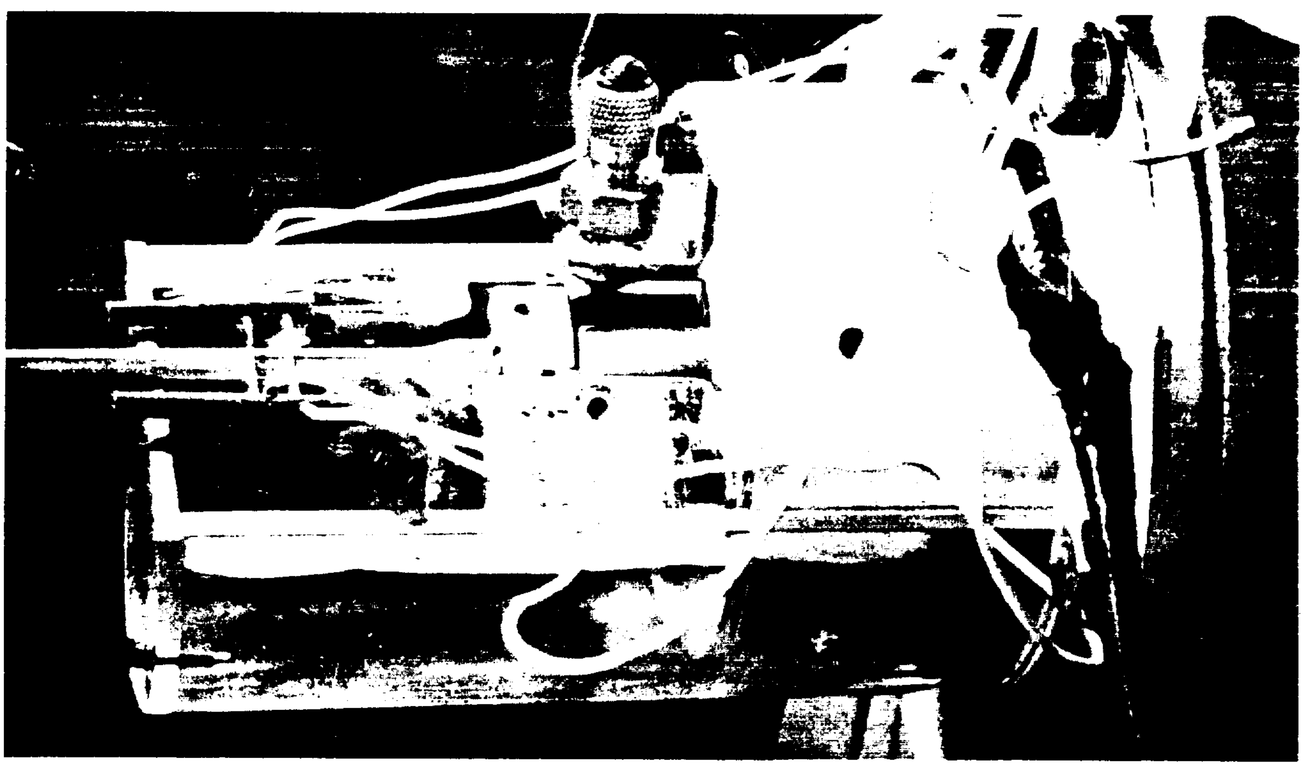


ENCLOSURE 11

WIRE BRUSH SLIP RINGS OPERATING INSIDE A PROTECTIVE ENCLOSURE ON A GOLD PLATED QUILL



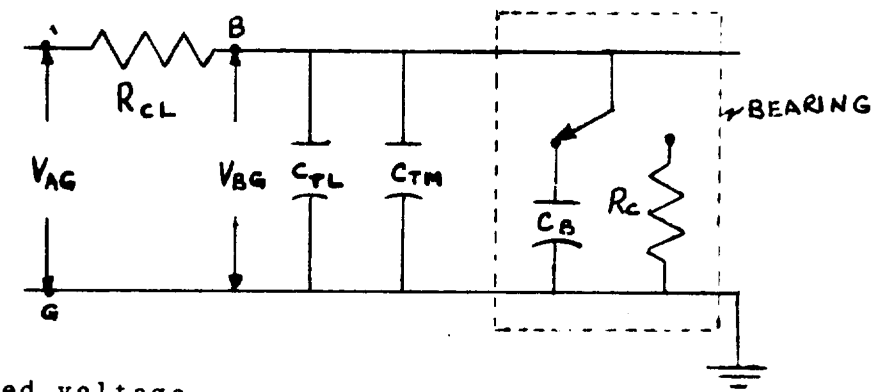
With Cover



Without Cover

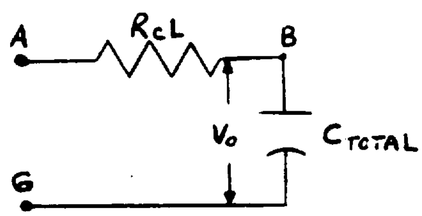
ENCLOSURE 12

BEARING EQUIVALENT CIRCUIT



V_{AG} = applied voltage
R_{CL} = current limiting resistance
C_B = capacitance of the bearing (parallel arrangement of 12 pairs of parallel plate capacitors
R_C = contact resistance during periods of asperity contact
C_{TL} = capacitance of all test leads
C_{TM} = capacitance of the test machine
V_{BG} = monitored voltage

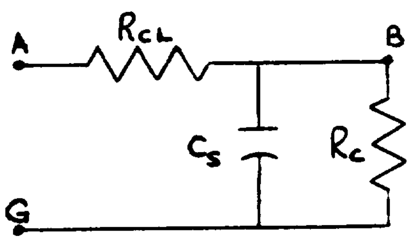
Bearing equivalent check under full EHD lubrication conditions (No asperity contact occurrences)



$$C_{TOTAL} = C_T = C_{TL} + C_{TM} + C_B$$

$V_c = V_{BG}$ during no contact

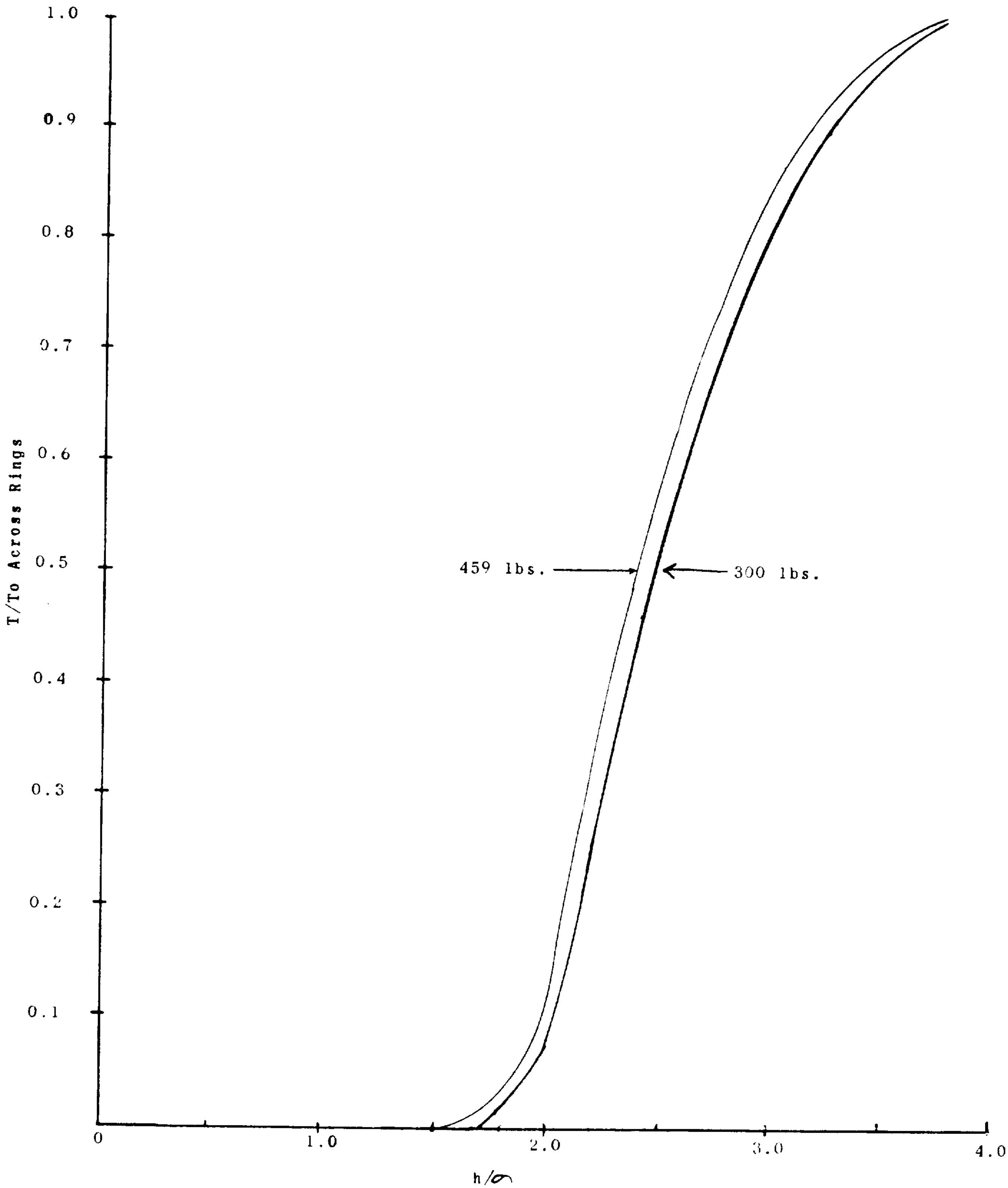
Bearing Equivalent check under partial EHD lubrication conditions (some asperity contact occurrences)



$$C_S = C_{TL} + C_{TM}$$

ENCLOSURE 13

GRAPH OF T/TO (ACROSS RINGS) VS. h/σ FOR A 7205 VAP TEST BEARING OPERATING AT A SPEED OF 43,000 RPM WITH A THRUST LOAD OF 459 AND 300 lbs.



ENCLOSURE 14

SPECIAL DUPONT POLYIMIDE SP-1 CAGES

INNER AND OUTER LAND RIDING

FAILED

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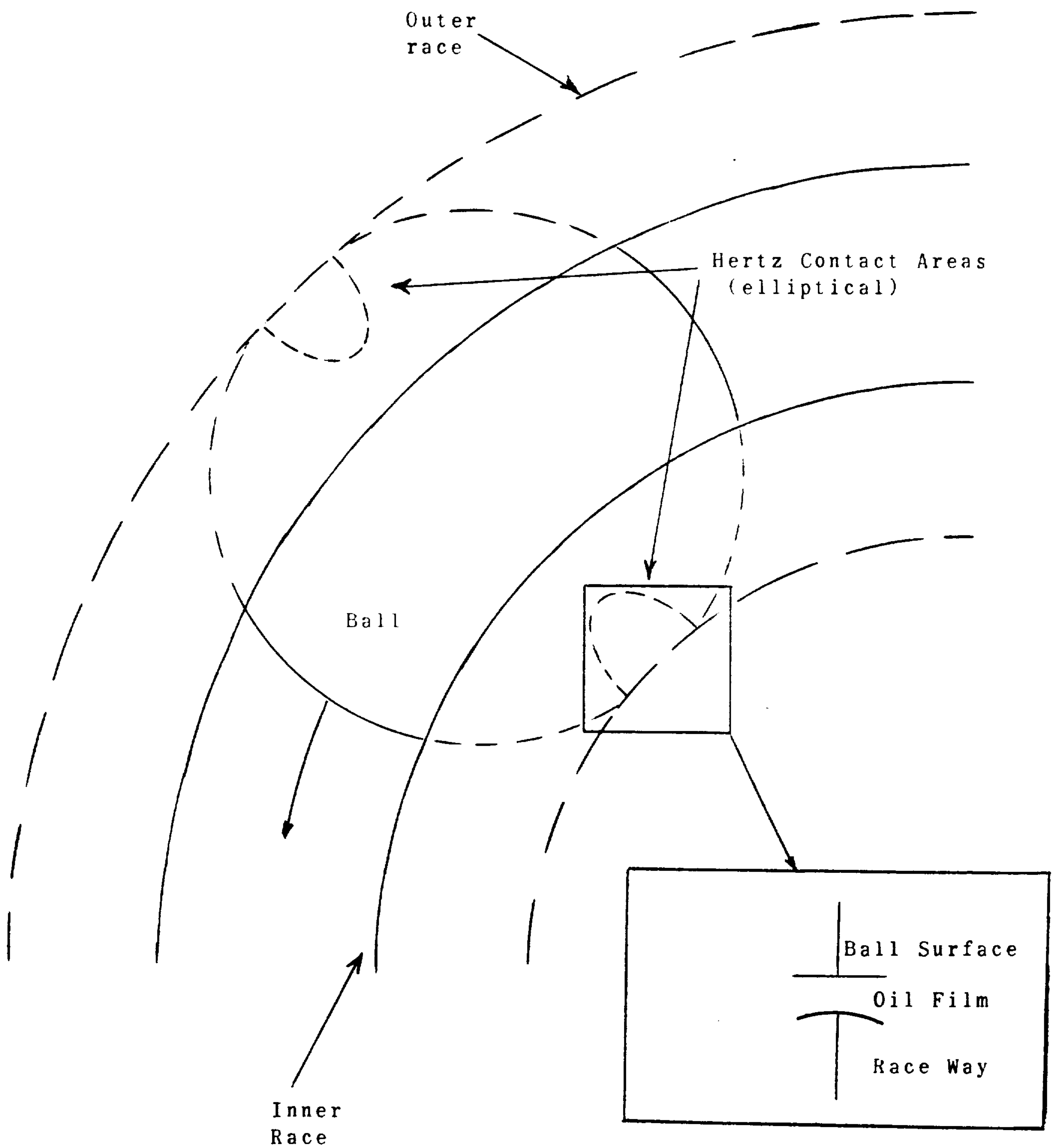
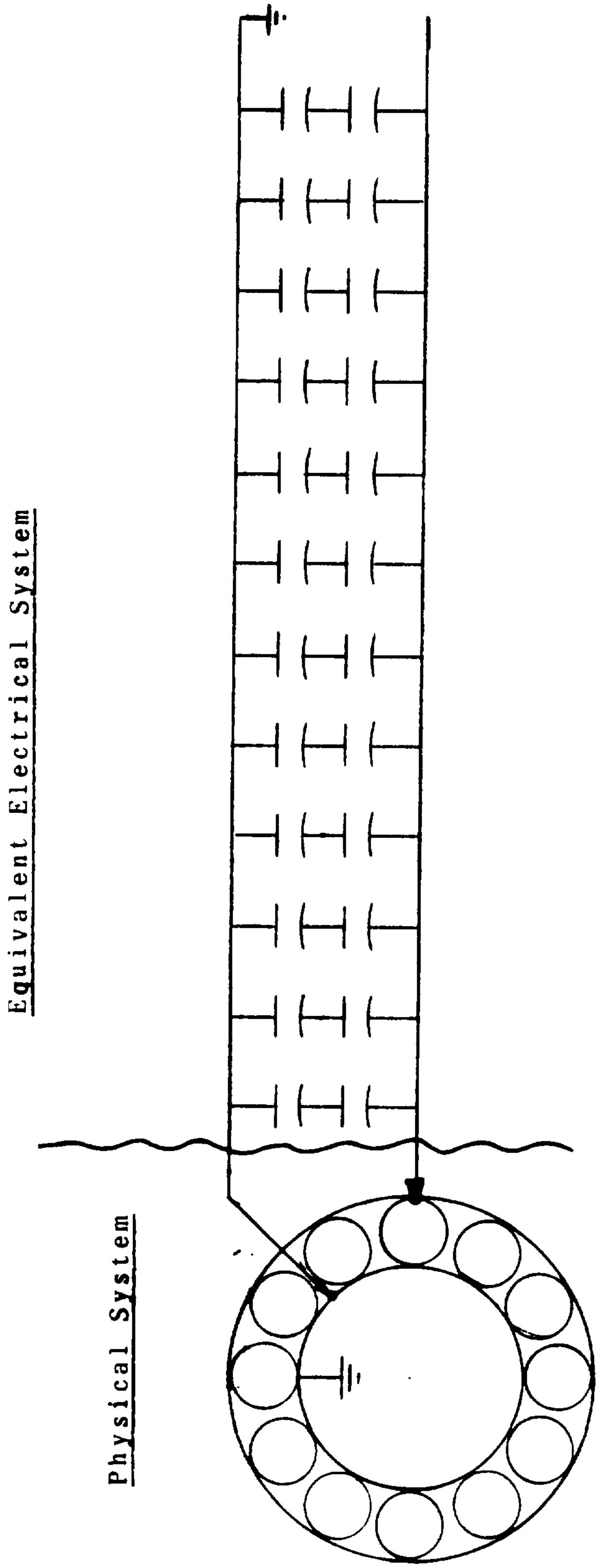
ENCLOSURE 15A

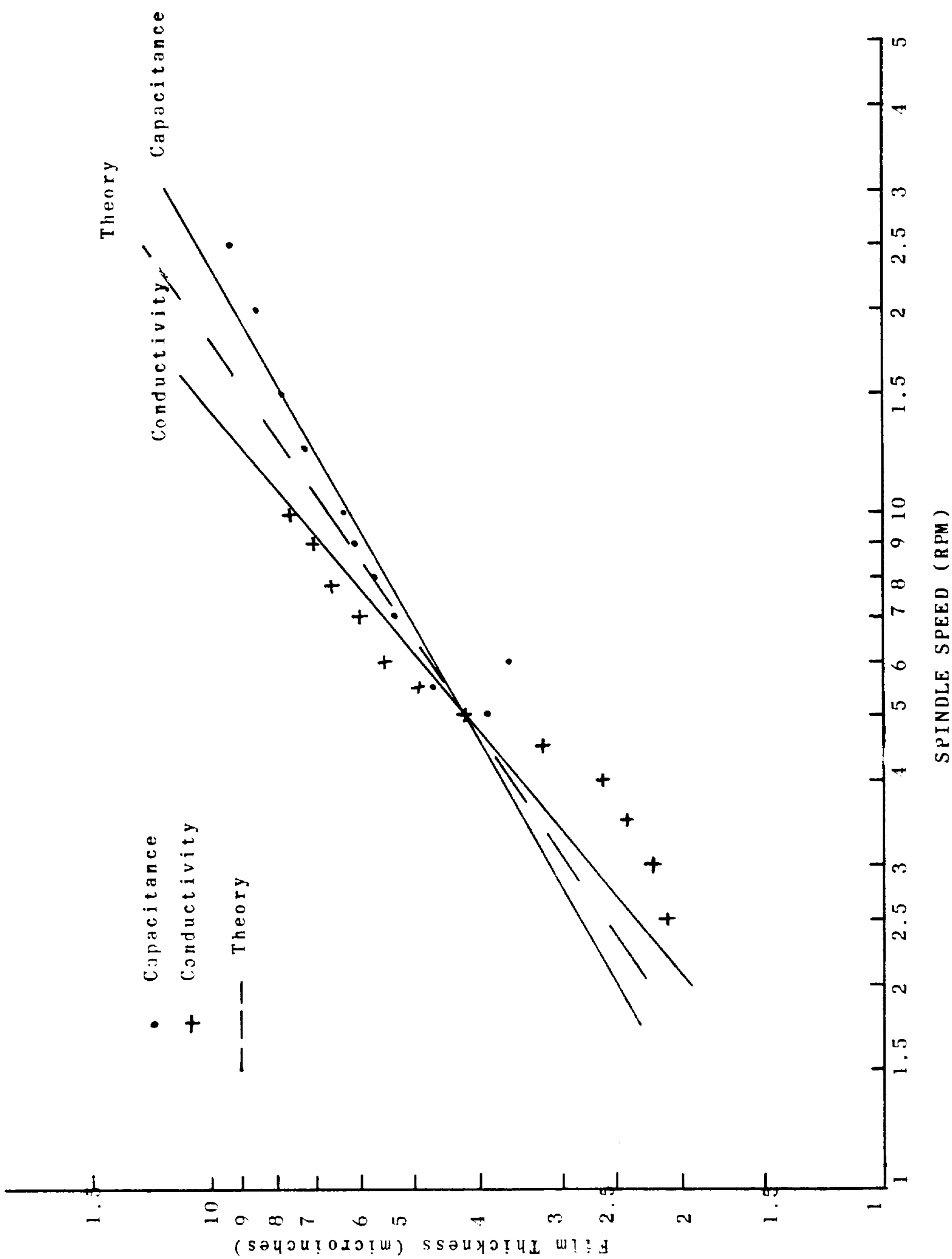
PROFILE OF INDIVIDUAL HERTZIAN
CONTACT AREAS IN OPERATING BALL BEARING



7205 BEARING EQUIVALENT CIRCUIT
UNDER FULL EHD LUBRICATION CONDITIONS

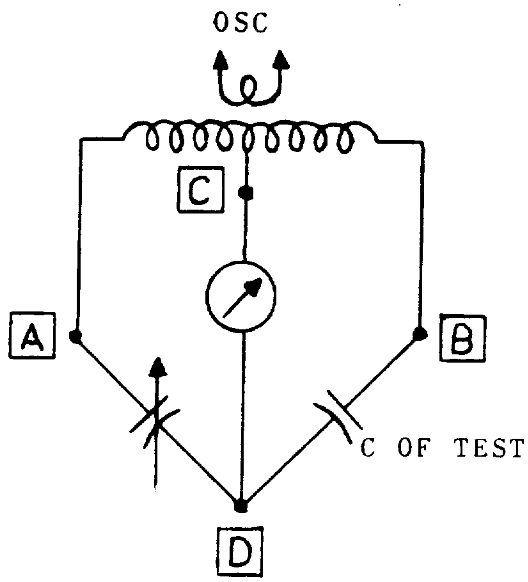


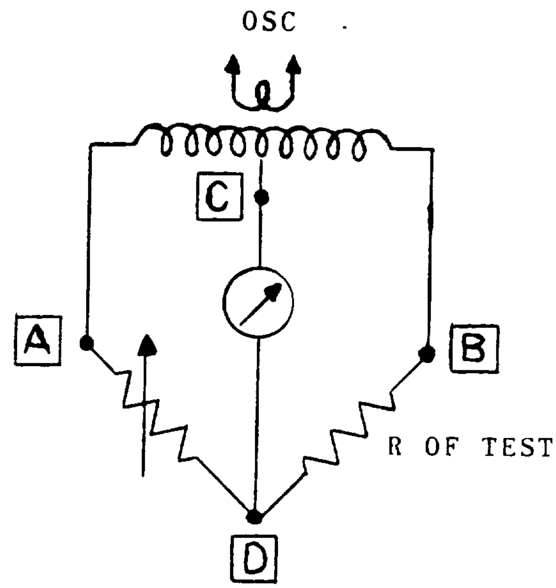
FILM THICKNESS AS A FUNCTION OF 4-BALL TESTER SPINDLE SPEED (INCREASING SPEED)



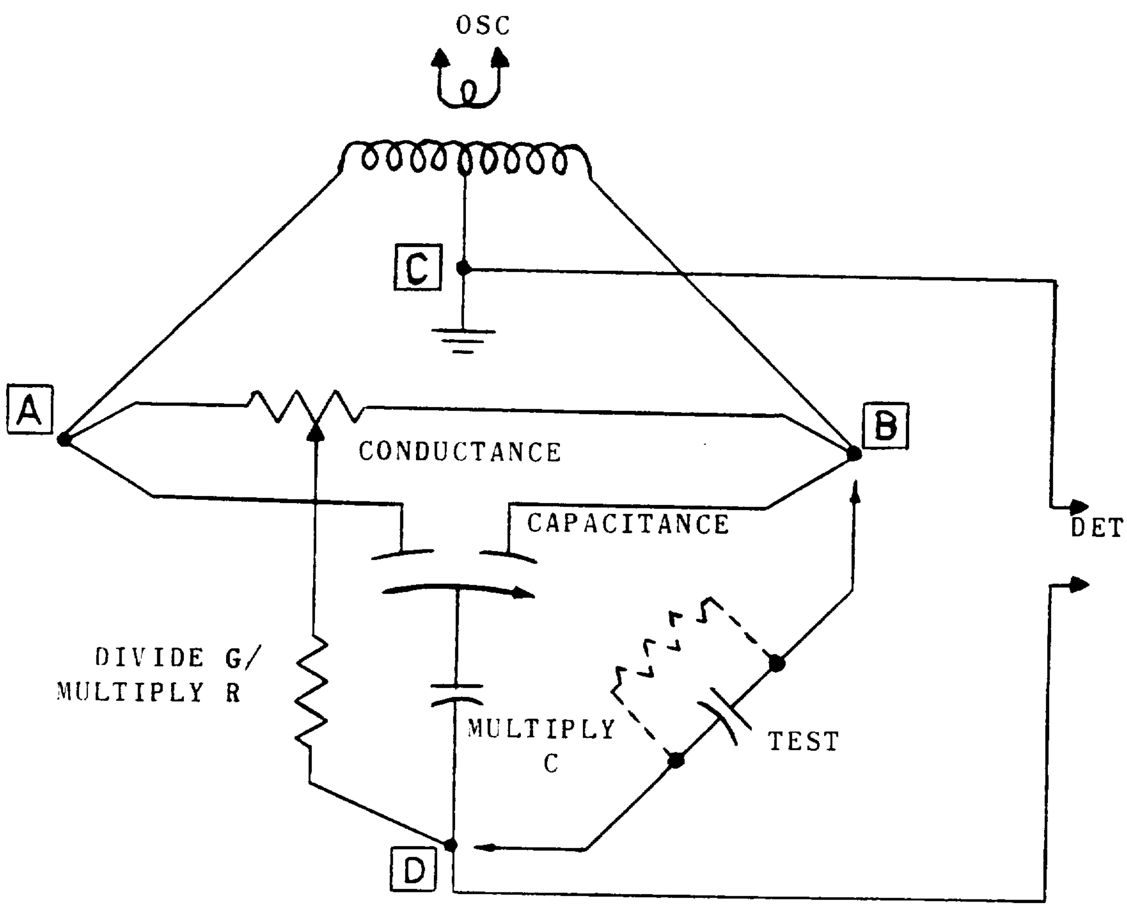
ENCLOSURE 17

SIMPLIFIED SCHEMATIC OF CAPACITANCE BRIDGE





BASIC BRIDGE CIRCUITS FOR C AND R



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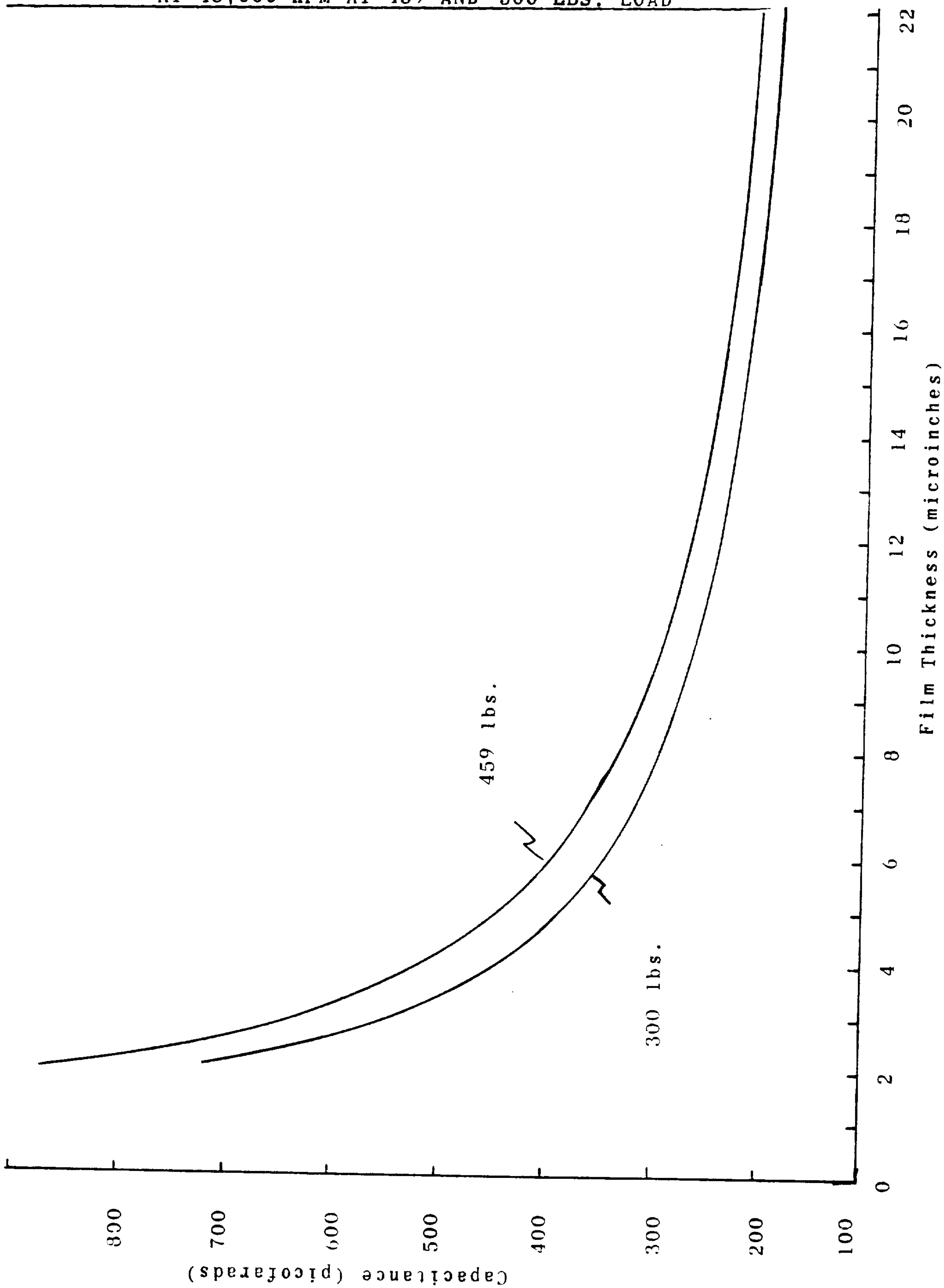
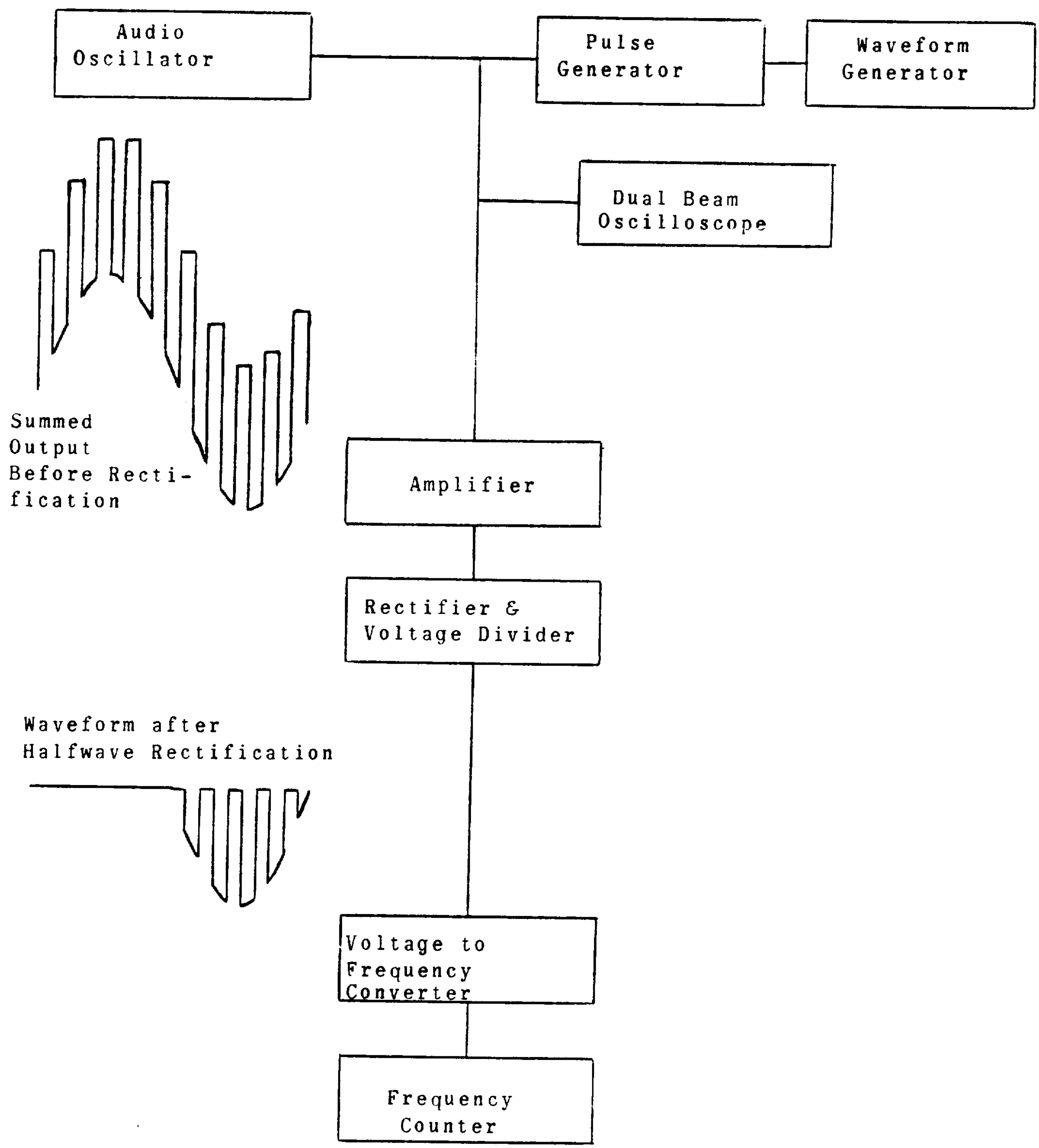
ENCLOSURE 18

GRAPH OF CAPACITANCE VS FILM THICKNESS FOR 7205 VAP BEARING AT 43,000 RPM AT 459 AND 300 LBS. LOAD



ENCLOSURE 19

GENERATION OF CONTACT ANALOG FOR CONTACT CONDUCTIVITY SYSTEM CHECK



ENCLOSURE 20

TABULATION OF READOUT VALUES FOR SIMULATED CONTACT OCCURRENCE WAVEFORMS

Pulse Frequency	Pulse Duration	Digital Readout	Expected Value	Expected Value-Digital Readout / Expected Value
10 KHz	3 usec	3.2%	3%	6.7%
10 KHz	5 usec	4.9%	5%	2.0%
10 KHz	10 usec	9.6%	10%	4.0%
10 KHz	15 usec	15 %	15%	0%
10 KHz	20 usec	19.6%	20%	2.0%
10 KHz	30 usec	29.3%	30%	2.3%
10 KHz	50 usec	50.4%	50%	.8%
1 KHz	5 usec	0.46%	.5%	8.0%
1 KHz	10 usec	0.96%	1.0%	4.0%
1 KHz	15 usec	1.41%	1.5%	6.0%

Note:

Input sinusoid at 2 v P-P at a frequency of 500 Hz
Vidar scale at 1000 mv maximum output

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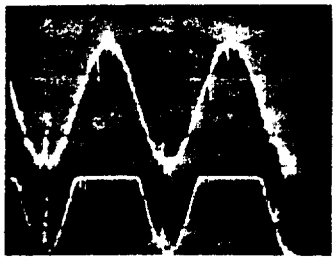
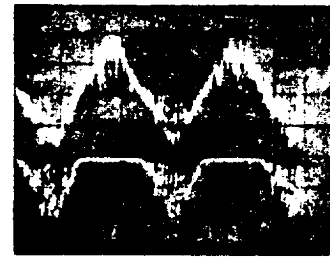
ENCLOSURE 21

PHOTOGRAPHS OF TYPICAL ELECTRICAL CONTACT CONDUCTIVITY WAVE FORMS AT VARIOUS V/VO RATIOS WITH A 5 KILOHM RESISTANCE (BEFORE AND AFTER RECTIFICATION)

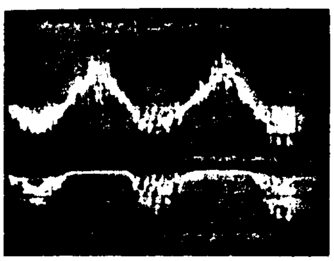


Temp. = 297°F
V/Vo measured=94%

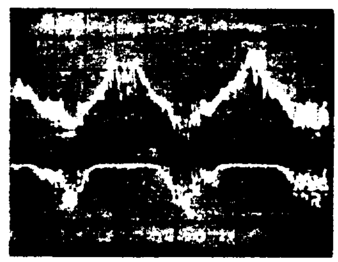
Temp.=322°F
V/Vo = 75%



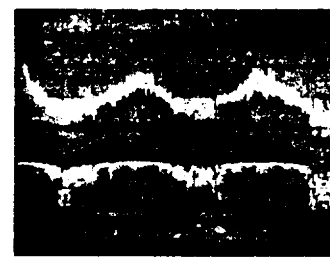
Temp.=341°F
V/Vo=56%



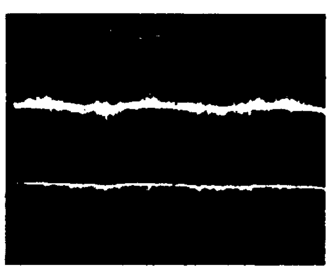
Temp.=351°F
V/Vo = 32%



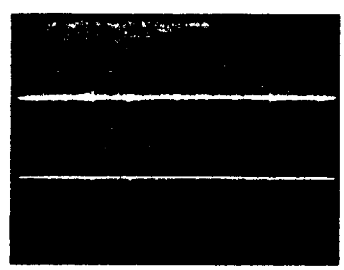
Temp.=400°F
V/Vo = 34%



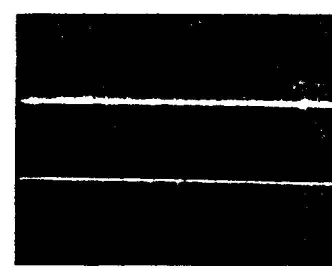
Temp.=415°F
V/Vo = 18%



Temp.=450%F
V/Vo = 4%



Temp. = 500°F
V/Vo = < 1%



Temp. = 550°F
V/Vo = < 1%

Amplification:	Vertical	Horizontal
Before Rectification	0.05 volts/div.	0.5 m sec/div.
After Rectification	0.02 volts/div.	0.5 m sec/div.

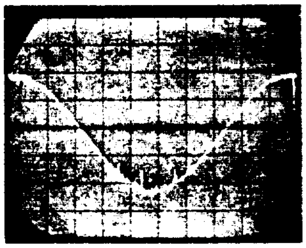
Note 1: Time travels right to left in photographs.
Note 2: Oscillograms shown above are from test reported in (13). Speed - 20,000 rpm, thrust load - 345 lbs., lubricant-Mobil XRM109F

ENCLOSURE 22

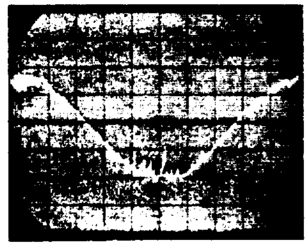
OSCILLOGRAMS OBTAINED IN TESTING WITH A 7205 VAR (WB-49 STEEL) BEARING AND DUPONT PR-143 LUBRICANT AT 459 LBS. THRUST LOAD AND TWO SPEEDS

5KΩ | 10KΩ | 50KΩ

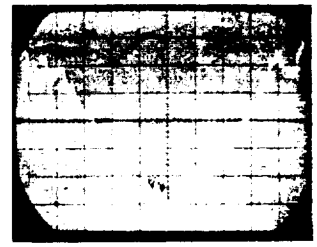
A. 24,000 RPM



550°F
V/V$_o$ = 90.5 h/σ = 3.4
* V = 0.5 H = 0.2

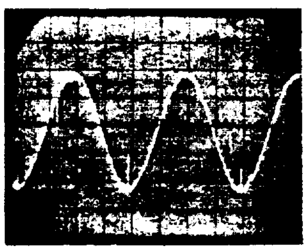


580°F
V/V$_o$ = 78.4 h/σ = 3.0
V = 0.5 H = 0.2

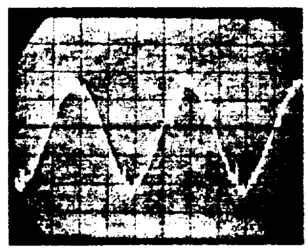


600°F
V/V$_o$ = 24.5 h/σ = 2.2
V = 0.2 H = 0.2

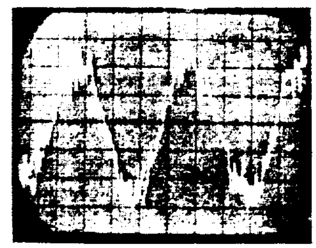
B. 24,000 RPM



560°F
V/V$_o$ = 91.8 h/σ = 3.4
V = 0.5 H = 0.5

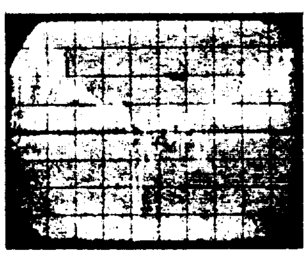


590°F
V/V$_o$ = 78.7 h/σ = 3.0
V = 0.5 H = 0.5

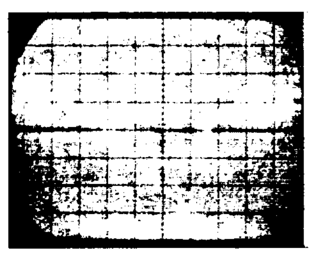


600°F
V/V$_o$ = 24.1 h/σ = 2.2
V = 0.2 H = 0.5

C. 39,000 RPM



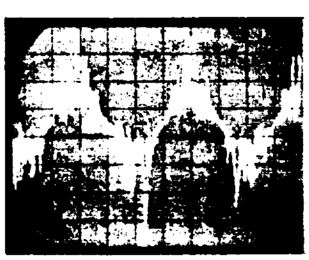
650°F
V/V$_o$ = 2.44 h/σ = 1.9
V = 0.1 H = 0.2



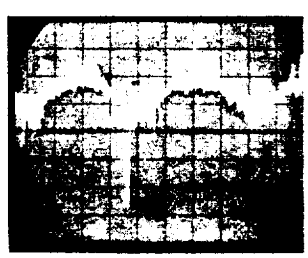
650°F
V/V$_o$ = <1 h/σ = —
V = 0.1 H = 0.2

650°F
V/V$_o$ = <1 h/σ = —
V = 0.05 H = 0.2

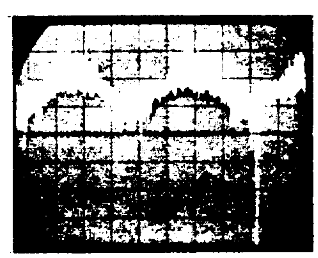
D. 39,000 RPM



650°F
V/V$_o$ = 2.04 h/σ = 1.9
V = 0.1 H = 0.5



650°F
V/V$_o$ = <1 h/σ = —
V = 0.2 H = 0.5



650°F
V/V$_o$ = <1 h/σ = —
V = 0.05 H = 0.5

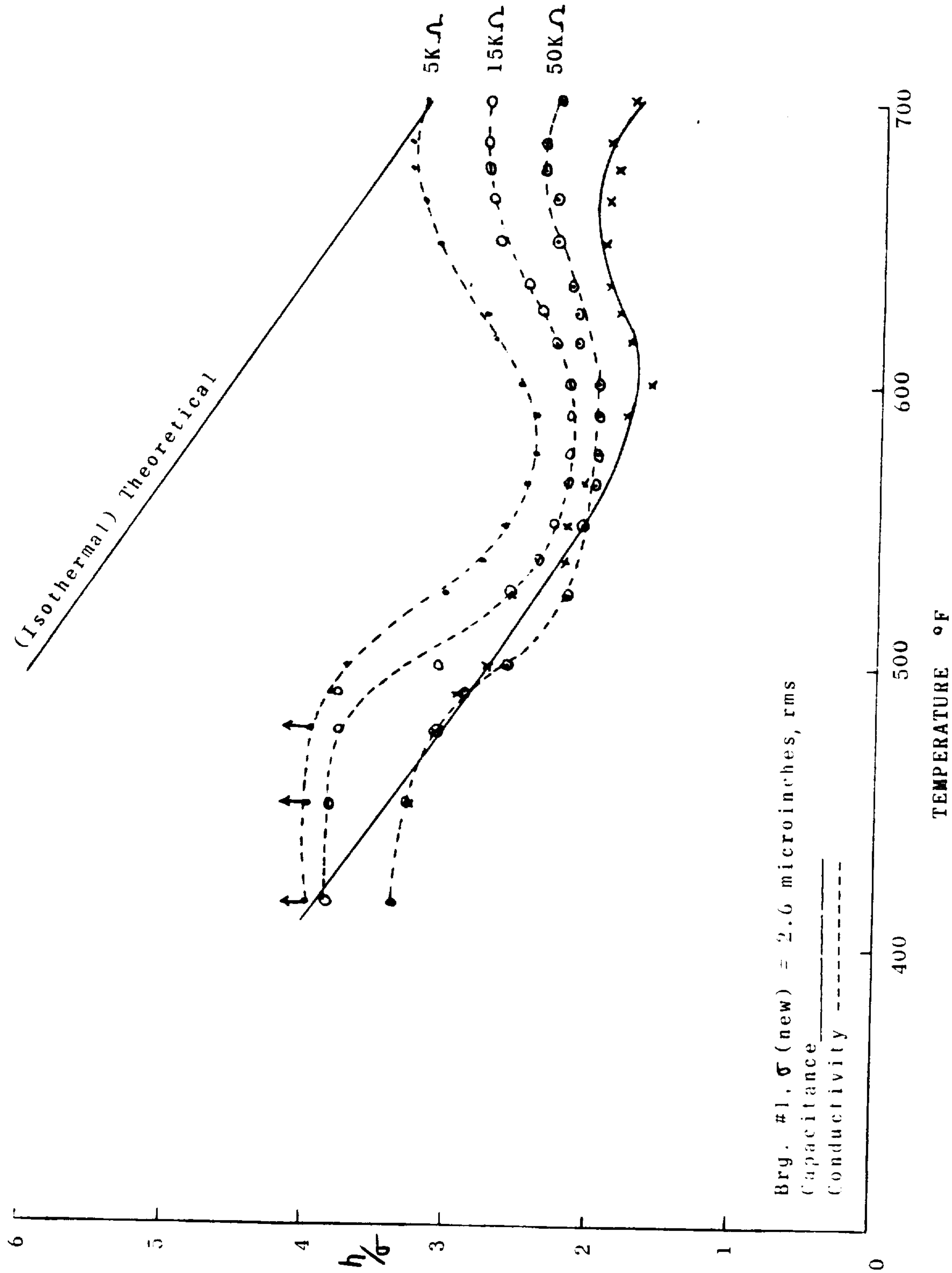
* Note 1: Amplitudes are given in volts/div. (vertical) and milliseconds/div.(Horizontal)
Note 2: Time travels right to left on photographs.

ENCLOSURE 23

PLOTS OF h/σ VS. TEMPERATURE OBTAINED WITH THE CONDUCTIVITY AND CAPACITANCE MEASURING SYSTEMS

(Test No. 2A., Ref. 13)

Test Conditions: Speed - 43,000 rpm, thrust load - 300 lbs., Lubricant - Mobil XRM-109F



ENCLOSURE 24

Measurement Data for the h/σ Vs. Temperature Plots of Enclosure 23 (Test No. 2A; Ref. 13)

Bearing σ Value = 2.6 microinches, rms.

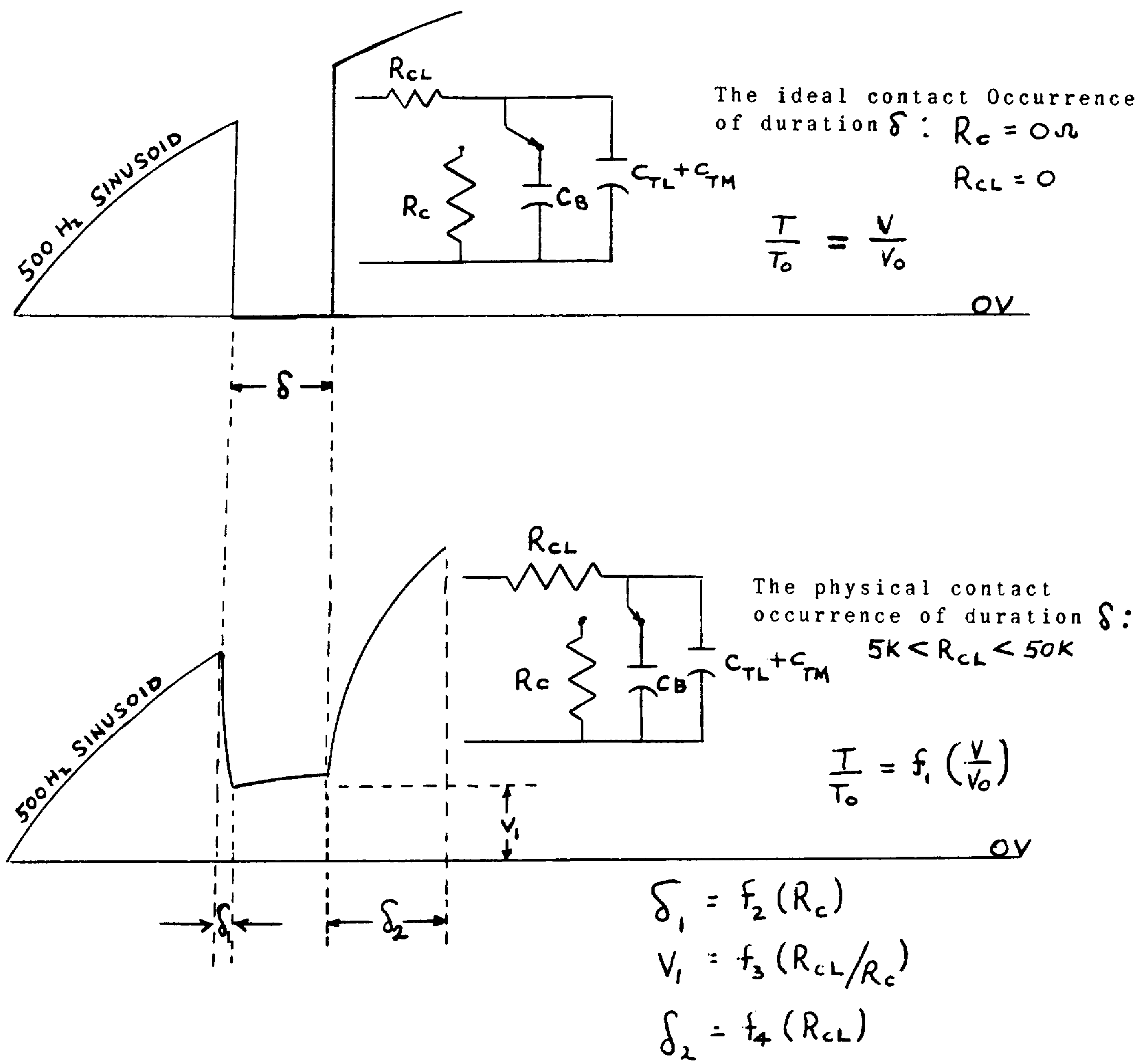
TIME (Hrs)	BEARING TEMP. °F	BRG. CAPACITANCE (PF)	h (μ in.)	h/σ	CONDUCTIVITY T/To 5KΩ	15KΩ	50KΩ	h/σ 5KΩ	15KΩ	50KΩ
7.2	415	224	10.2	4.0	100	98	91	4.0	3.9	3.4
7.25	450	259	8.5	3.3	100	98	89	4.0	3.9	3.3
7.3	477	270	8.0	3.1	100	96	85	4.0	3.8	3.1
7.35	490	282	7.7	3.0	98	95	80	3.9	3.8	2.9
7.4	500	300	7.1	2.8	97	86	61	3.8	3.1	2.6
7.6	525	317	6.7	2.6	83	59	22	3.0	2.6	2.2
7.7	537	365	5.7	2.2	74	43	15	2.8	2.4	2.2
7.8	550	364	5.7	2.2	65	33	10	2.7	2.3	2.1
7.9	565	385	5.4	2.1	53	23	6	2.5	2.2	2.0
8.0	575	396	5.2	2.0	51	21	6	2.5	2.2	2.0
8.1	589	439	4.6	1.8	49	21	6	2.4	2.2	2.0
8.25	600	482	4.2	1.6	58	27	8	2.6	2.2	2.1
8.45	615	442	4.6	1.8	69	38	14	2.7	2.3	2.1
8.55	626	418	4.8	1.9	74	45	17	2.8	2.4	2.2
8.65	635	412	5.9	1.9	79	53	23	2.9	2.5	2.2
8.75	650	403	5.1	2.0	86	63	32	32	2.7	2.3
8.85	665	409	5.0	1.9	89	70	39	3.3	2.8	2.3
9.0	677	415	4.9	1.9	91	74	44	3.4	2.8	2.4
9.1	685	413	5.0	1.9	91	74	42	3.4	2.8	2.4
9.3	700	435	4.6	1.8	89	69	38	3.3	2.8	2.3

Test Conditions: Speed - 43,000 rpm, Thrust Load - 300 lbs.,
Lubricant - Mobil XRM-109F

F 4186A R100

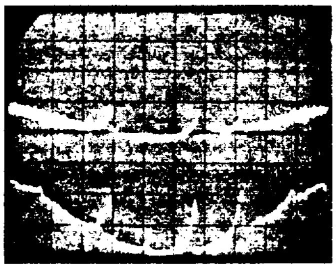
ENCLOSURE 25

THE "IDEAL" AND EXPERIMENTAL CONTACT OCCURENCE

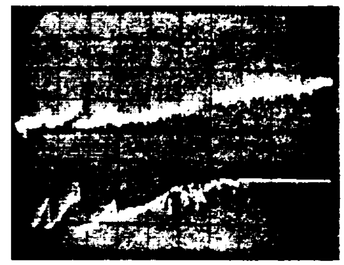


ENCLOSURE 26

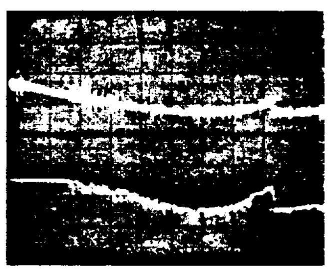
PHOTOGRAPHS OF CONTACT OCCURRENCES OBTAINED USING VALUES OF CURRENT LIMITING RESISTANCES OF 5, 15, AND 50 KILOHMS
(Before and After Rectification)



5 Kohms
Temp.=290°F
V/Vo measured = 96%



15 Kohms
Temp.= 303°F
V/Vo measured = 84%



50 Kohms
Temp.= 314°F
V/Vo measured = 51%

Application:	Vertical	Horizontal
Before Rectification	0.1 Volts/Div.	0.2 msec/Div.
After Rectification	0.2 Volts/Div.	0.2 msec/Div.

Note 1: Time travels from right to left on photographs
Note 2: Oscillograms shown above are from tests reported in (13). Speed - 20,000 rpm, thrust load-345 lbs., lubricant-Mobil XRM-109F